U.S. Department of the Interior
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FEASIBILITY OF USING GROUND WATER AS A SUPPLEMENTAL SUPPLY FOR BROOKLYN AND QUEENS, NEW YORK

Water-Resources Investigations Report 98-4070

Prepared in cooperation with the

NEW YORK CITY DEPARTMENT OF ENVIRONMENTAL PROTECTION AND

THE NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION

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U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply inch-pound unit	**By**	**To obtain metric unit**
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	square hectometer (hm^2)
gallon (gal)	3.785	cubic meter (m^3)
billion gallons	3,785,000	cubic meter (m^3)
foot per day (ft/d)	0.3048	meter per day (m/d)
million gallons per day (Mgal/d)	3,785	cubic meters per day (m^3/d)

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Feasibility of Using Ground Water as a Supplemental Supply for Brooklyn and Queens, New York

By Herbert T. Buxton, Douglas A. Smolensky, and Peter K. Shernoff

ABSTRACT

New York City derives 1.5 billion gallons of water per day from a system of 18 upstate surface-water reservoirs. Periodic droughts in recent decades have resulted in temporary, but severe, depletion of these reservoirs. Among several proposed solutions is the development of the ground-water resources beneath the boroughs of Brooklyn and Queens on Long Island as an emergency supplement.

A three-dimensional model of the Long Island ground-water system was used to evaluate the effects of short-term ground-water withdrawals at various rates under recent (early 1980's), stressed conditions and a hypothetical "full-reservoir" condition, in which the ground-water system is maintained at its maximum storage capacity. The allowed pumping duration for each rate was defined as the interval from the start of pumping until simulated ground-water levels were drawn down to near sea level. Short-term and intensive ground-water pumping maximizes the quantity of the ground-water supplement while minimizing the corresponding reduction in base flow and effects on the saltwater-freshwater interface.

Ground-water supplements simulated under recent stressed conditions ranged from 22.8 billion gallons (pumping for 15 months at 50 million gallons per day) to 14.1 billion gallons (pumping for 3.1 months at 150 million gallons per day). The estimated decrease in discharge to ground-water system boundaries did not exceed 15.6 million gallons per day (about 31 percent of the pumping rate) for the 22.8 billion-gallon supplement, and did not exceed 10.5 million gallons per day (7 percent of the pumping rate) for 14.1 billion-gallon supplement. Results indicate that these supplements could be implemented once every 5 to 6 years allowing natural recovery or once every 2 or 3 years using artificial recharge of surplus surface water to accelerate ground-water level recovery.

Under the "full-reservoir" condition, supplements ranged from 64.5 billion gallons (pumping for 10.6 months at 200 million gallons per day) to 37.2 billion gallons (pumping for 3.1 months at 400 million gallons per day). The estimated decrease in discharge to ground-water system boundaries did not exceed 35.3 million gallons per day (about 18 percent of the pumping rate) for the 64.5 billion-gallon supplement and did not exceed 21.3 million gallons per day (about 5 percent of the pumping rate) for the 37.2 billion-gallon supplement. These rates could be implemented once every 5 to 7 years allowing natural recovery or once every 3 to 4 years using artificial recharge.

During droughts, the appropriate ground-water-pumping rate and duration could be selected based on specific reservoir conditions--supplying an immediate source of water at a high rate during times of critically low reservoir levels, or supplying a supplement of moderate rate and larger total volume that emphasizes reservoir recovery to year-end capacity. Such a conjunctive-use strategy could mitigate water shortages during periods of drought while conserving ground-water resources.

INTRODUCTION

New York City uses an extensive upstate reservoir system that contains 18 reservoirs and three controlled lakes and has a storage capacity of 548 billion gal (gallons). Periodic droughts that affect the upstate reservoir system have resulted in dangerously low storage volumes in these reservoirs. The frequency of drought emergencies has increased in recent decades, and the threat of a severe water-supply emergency is ever present. Increased awareness of the susceptibility of the city's water supply to droughts has resulted in efforts to identify possible methods of meeting these needs. Among several proposed solutions is the possibility of developing a conjunctive-use water-supply strategy that uses the ground-water system beneath Brooklyn and Queens as a supplemental source.

Although surface-water-supply systems typically are vulnerable to depletion during seasonal droughts, the Long Island ground-water system responds more slowly and is not affected until drought conditions become prolonged (Cohen and others, 1969). The feasibility of using ground water to supplement the surface-water supply will depend not only on the quantity of ground water available, but on the duration and the frequency at which it could be pumped without causing unacceptable adverse effects.

Brooklyn and Queens are boroughs of New York City. They are located on the western end of Long Island, and are separated from the other boroughs (Staten Island, Manhattan, the Bronx), which lie to the west and north, by New York Bay, the East River, and Long Island Sound (fig. 1). Nassau and Suffolk Counties, the remainder of Long Island, lie to the east. Brooklyn and Queens together contain 189 mi^2 (square miles), (76 mi^2 and 113 mi^2, respectively). In 1990, the population of Brooklyn was 2.3 million, and that of Queens was 1.95 million.

Purpose and Scope

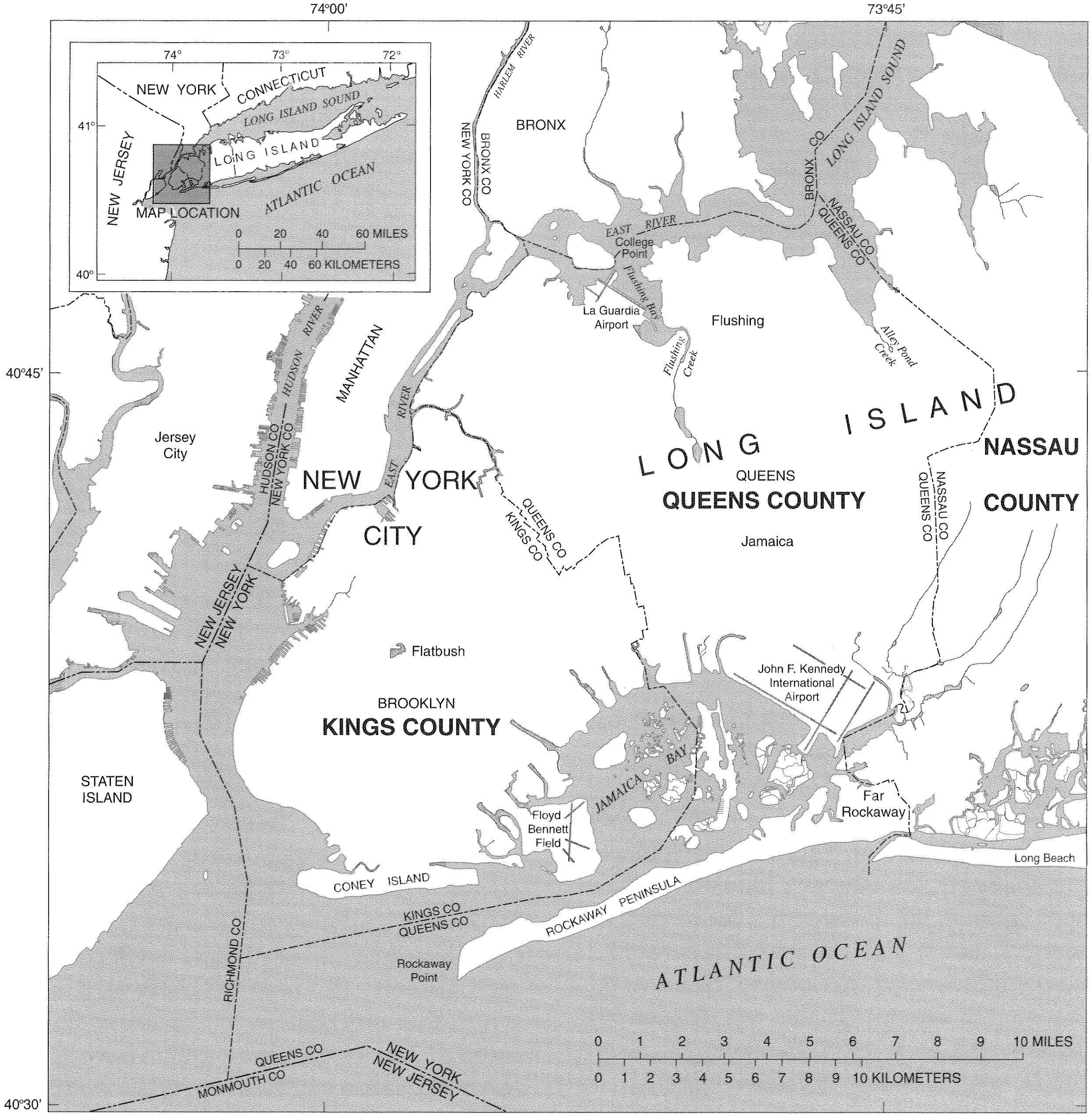
The analysis presented herein assesses the feasibility of using ground water from Brooklyn and Queens to supplement New York City's upstate surface-water supply during periods of extreme low reservoir levels caused by drought. A three-dimensional model of the Long Island ground-water flow system is used to evaluate the system's sensitivity to short-term ground-water withdrawal scenarios. The results of simulations provide a means to evaluate practical pumping rates, pumping durations, and recovery times between subsequent episodes of supplemental pumping. Decreases in ground-water levels and discharge to boundaries (streams and the shoreline) provide a measure of the adverse effects of ground-water pumping.

The purpose of this report is to demonstrate a range of practical alternatives for such a conjunctive-use water-supply strategy under recent (early 1980's) stressed conditions and a hypothetical "full-reservoir" condition. Recovery times for the ground-water system are estimated considering natural recovery and recovery accelerated by artificial recharge of subsequent surface-water surpluses.

Although the accuracy of the predictive model simulations used herein cannot be specifically defined, a comparative analysis of the sensitivity of the system to various pumping scenarios provides a sound basis for evaluating the feasibility of a conjunctive-use supplemental water-supply strategy.

Basis for Conjuntive-Use Strategy

Fundamental to such a conjunctive-use water-supply strategy is the fact that, ground-water systems respond more slowly to drought than surface-water reservoirs, and can retain significant storage when reservoirs are depleted. In addition, ground-water withdrawals initially are derived largely from ground-



Base modified from U.S. Geological Survey, 1:100,000;
Long Island West, New York—New Jersey—Connecticut,1984;
Newark, New Jersey—New York, 1986

Figure 1. Location and principal geographic features of the boroughs of Brooklyn and Queens, New York City

water storage, and, for short-term withdrawals, the maximum decrease in the rate of boundary discharge is only a small fraction of the pumping rate. Ultimately, after cessation of pumping and complete recovery of the ground-water system, the volume of water pumped is balanced by an equivalent decrease in the volume of water discharged at ground-water system boundaries (streams and the shore). However, the decrease in discharge to boundaries caused by the period of pumping is dispersed over the periods of pumping and recovery.

History of Water Use

Ground water was the first source of water supply on western Long Island. Early European settlers obtained water from shallow wells and ground-water-fed streams and springs. As the population grew, ground-water use increased rapidly. By the mid-19th century, combined storm and sanitary sewers with ocean outfall had been constructed in populated areas of Brooklyn, causing most of the water pumped to be lost from the ground-water system. As a result, saltwater intrusion into the aquifers developed in nearshore areas before the turn of this century (Spear, 1912).

To meet the rapidly increasing demand for water supply throughout New York City, a large surface reservoir system was developed to the north in New York State that has supplied water to Manhattan since 1842. In 1917, the first tunnel to carry this water to Brooklyn was opened, and a second tunnel followed in 1936.

Ground-water use in Brooklyn and Queens also increased and, by 1930, reached a maximum of 150 Mgal/d. From 1904 to 1947, pumping for industrial use and public supply averaged 120 Mgal/d. This sustained pumping eventually caused saltwater intrusion in the upper glacial, the Jameco, and the Magothy aquifers, and in 1947, all pumping for public supply in Brooklyn was stopped as a result. Pumping in western Queens was stopped for the same reason in 1974. Pumping for public supply continues only in eastern Queens.

In the late 1980's, the reservoir system supplied an average of 1.5 billion gal per day for public supply, almost 700 Mgal/d of which was used in Brooklyn and Queens; in addition, about 62 Mgal/d is pumped by the JWSC (fig. 1) from aquifers in Queens to serve approximately 350,000 people. This is the only ground water used for public supply in New York City. Buxton and Shernoff (1995) provide additional information about the development of water supplies in Brooklyn and Queens.

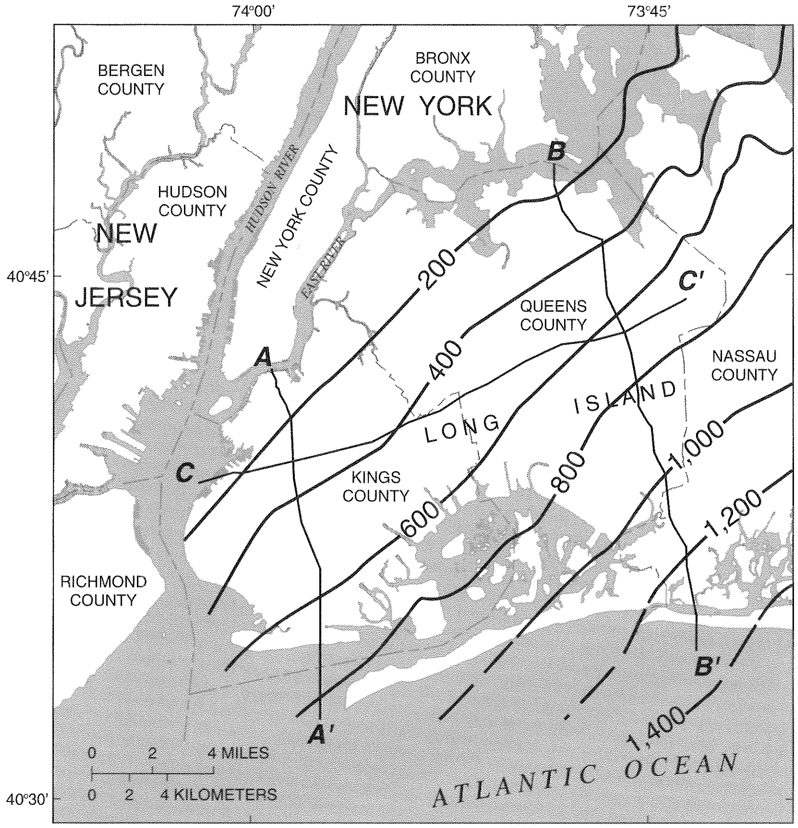
HYDROLOGIC SETTING

Hydrogeologic Framework

The ground-water system beneath Brooklyn and Queens consists of Cretaceous and Pleistocene age unconsolidated deposits underlain by crystalline bedrock. The unconsolidated deposits "pinch out" in northwestern Queens, where bedrock crops out, but attain a thickness of more than 1,000 ft (feet) in southeastern Queens (fig. 2).

The unconsolidated deposits form six distinct hydrogeologic units--four aquifers and two confining units--that generally dip south-southeastward (fig. 3). Table 1 describes the age and the stratigraphic relations of geologic units in western Long Island. Geologic units generally correspond to hydrogeologic units refered to throughout this report; these are, in ascending order, the Lloyd aquifer, the Raritan confining unit, and the Magothy aquifer (deposited during the Late Cretaceous Epoch) and the Jameco aquifer, the Gardiners Clay, and the upper glacial aquifer (deposited during the Pleistocene Epoch). The water-transmitting properties of these units are described in Buxton and Smolensky (1999). The confining units, the Raritan confining unit and the Gardiners Clay, have a vertical hydraulic conductivity of approximately 10^{-3} ft/d (feet per day), which is at least four orders of magnitude lower than the aquifers. The Pleistocene aquifers have horizontal hydraulic conductivity values of 200 to 300 ft/d and lower permeability in local zones associated with moraines and proglacial lakes; their anisotrophy is typically 5:1 to 10:1. The Cretaceous aquifers have horizontal hydraulic conductivities of 35 to 90 ft/d and considerably higher anisotropy (30:1-100:1) because of an abundance of discontinuous clay lenses.

The position, thickness, and extent of the hydrogeologic units beneath Brooklyn and Queens have a major effect on the patterns of ground-water movement. In most of Brooklyn,



EXPLANATION

B——**B'** Trace of hydrogeologic section

——800 – – – LINE OF EQUAL THICKNESS OF UNCONSOLIDATED DEPOSITS--
Dashed where approximately located. Contour interval 200 feet.

Figure 2. Thickness of unconsolidated deposits in western Long Island. (Modified from Buxton and others, 1989, fig. 2.)

the Gardiners Clay and the Raritan confining unit completely overlap underlying aquifers, which impedes vertical flow within the system (fig. 3, sections A-A' and C-C'). In Queens, the Gardiners Clay overlies the Magothy and the Jameco aquifers only in the southern part (fig. 3, section B-B'); elsewhere in Queens, ground water can move unimpeded between the upper glacial and the Jameco and Magothy aquifers. The Jameco and the Magothy aquifers function much as a single aquifer unit because the Jameco aquifer was deposited on the eroded and irregular Magothy surface and because these two aquifers are confined over a large area between the Raritan confining unit and the Gardiners Clay (fig. 3). These aquifers at times will be referred to as the composite Jameco-Magothy aquifer unit.

A major erosional channel that Soren (1978) interpreted to be an ancestral diversion of the Hudson River trends north-south from Flushing Bay to the center of Queens. This channel has eroded through the Magothy aquifer and the Raritan confining unit and forms a direct pathway for ground water to flow from the upper glacial aquifer to the Lloyd aquifer (fig. 3, section C-C').

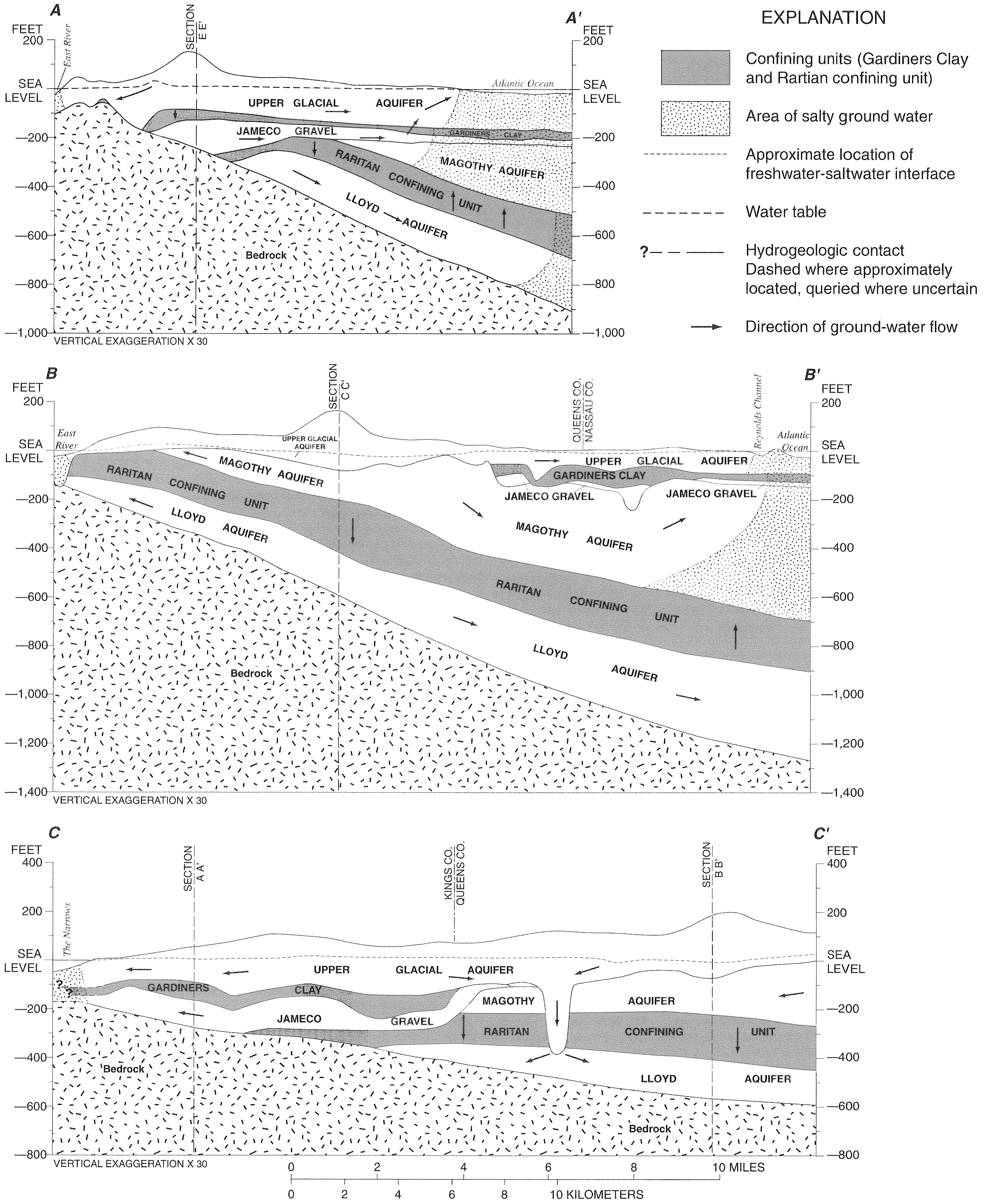


Figure 3. Hydrologic sections through the study area. (Locations are shown in figure 2.)

Table 1. Western Long Island stratigraphic column with geologic and hydrogeologic interpretation.

System	Series	Geologic Unit		Hydrogeo-logic unit	Range of thickness, in feet	Range of altitude of upper surface, in feet above sea level
QUATERNARY	Holocene	Shore, beach salt-marsh deposits, and alluvium				
	Pleistocene	Wisconsin Glaciation (Harbor Hill, interstadial marine and Ronkonkoma?) Drift	Includes: Till (ground and terminal moraine), Outwash, and the "20-foot" clay (marine)	Upper Glacial aquifer	0 to 300	Land surface
		Sangamon Interglaciation	Gardiners Clay (marine)	Gardiners Clay	0 to 150	-40 to -200
		Pre-Wisconsin Glaciation (Illinoian?)	Jameco Gravel	Jameco aquifer[1]	0 to 200	-90 to -240
CRETACEOUS	Upper Cretaceous	Magothy Formation and Matawan Group undifferentiated		Magothy aquifer[1]	0 to 500	40 to -400
		Raritan Formation	Clay member	Raritan confining unit	0 to 200	30 to -650
			Lloyd sand member	Lloyd aquifer	0 to 300	-90 to -825
Precambrian		Crystalline bedrock		Bedrock	–	15 to -1100

[1] The Magothy and Jameco aquifers are often considered as one hydrologic unit with differing hydraulic properties. (See discussion in text.)

Hydrologic Boundaries and Ground-Water Movement

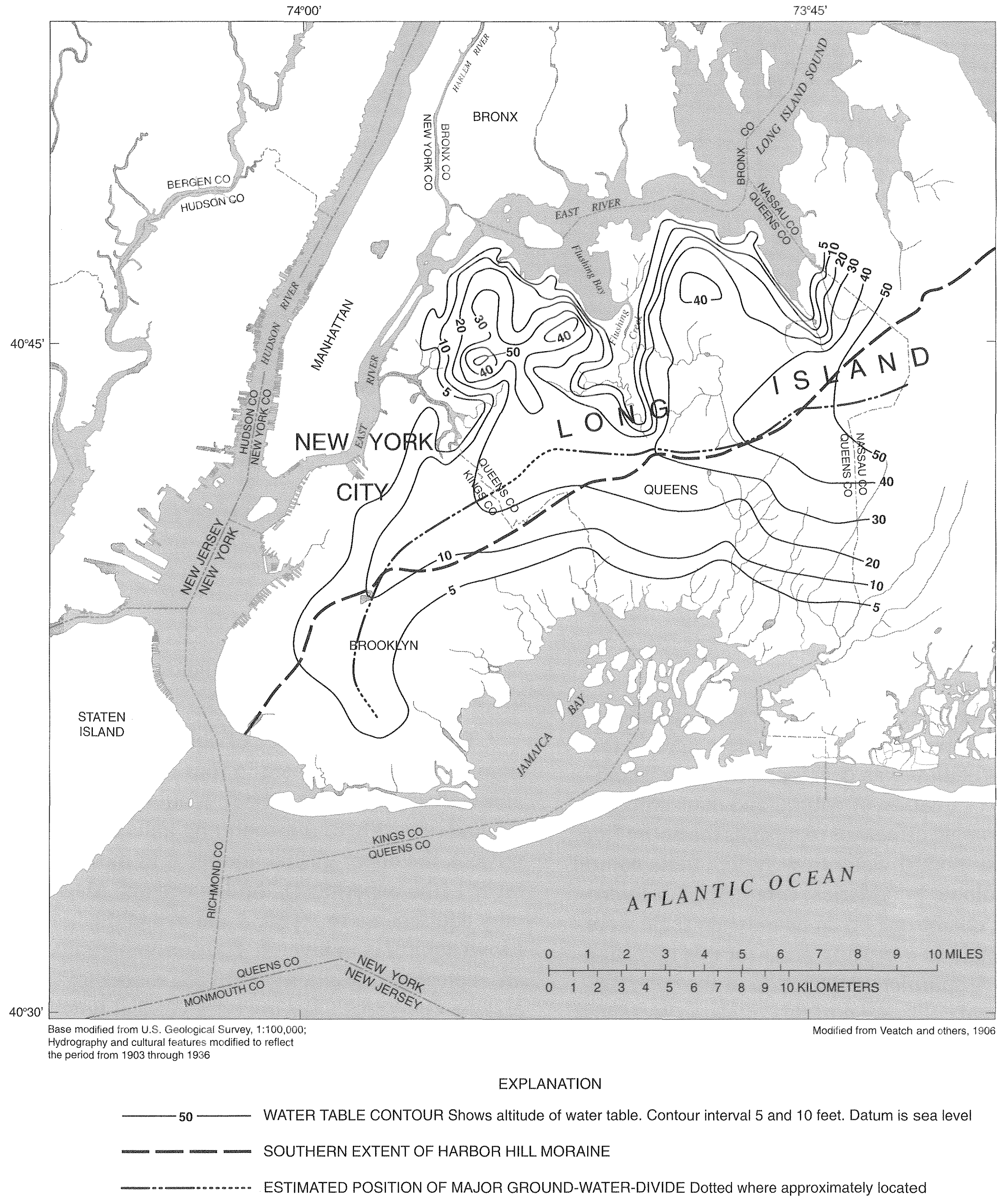
The boundaries of the fresh ground-water system are the water table and ground-water-fed streams on top, impermeable bedrock on the bottom, and the contact with salty ground water or salty surface-water bodies on all sides (fig. 3). Before development, all water entered the system at the water table (fig. 4) as recharge from precipitation; a small amount of ground water flowed westward into Queens from Nassau County. The predevelopment water table indicates ground-water movement laterally toward discharge to stream channels and the shore. The asymmetric shape of the water table indicates that more ground water flowed southward than to the northern shore -- a result of (1) the lower permeability of moraine deposits that characterize the northern part of the upper glacial aquifer, (2) the "pinching out" of the water table aquifer by the underlying low permeability units (the bedrock and the Raritan confining unit (fig. 3, sections A-A' and B-B')), and (3) the greater number of ground-water-fed streams along the southern shore than the northern shore, a topographic effect (fig. 4). Some ground water flowed down to the Jameco and the Magothy aquifers (fig. 3), particularly where the Gardiners Clay is absent, then flowed laterally seaward and discharged offshore, where it mixed with salty ground water that overlies the Gardiners Clay (subsea discharge).

Only a small amount of ground water flowed down to the Lloyd aquifer, although the eroded channel through the Raritan confining unit undoubtedly was a major source of recharge to it (fig. 3, section C-C'). Fresh ground water in the Lloyd aquifer extended several miles off the island's southern shore and discharged to the salty ground water that overlies the Raritan confining unit (subsea discharge). A detailed discussion of the ground-water system beneath Brooklyn and Queens is given in Buxton and Shernoff (1995). A model simulation of predevelopment conditions (Buxton and Smolensky, 1999) indicates that of 164 Mgal/d entering Brooklyn and Queens, largely by recharge from precitation, 58 Mgal/d discharges to streams and the remaining 106 Mgal/d discharges to subsea boundaries (see table 2, p. 14).

FEASIBILITY OF USING GROUND WATER AS A SUPPLEMENTAL SUPPLY

The simulation analysis of the feasibility of using ground water to supplement periodic surface-water supply shortfalls is presented in four parts.

- A simulation of the initial stressed equilibrium condition representative of the early 1980's is described.
- Simulations of the effects of supplemental pumping scenarios under recent stressed conditions are presented. During this condition, an average of 61 Mgal/d is being pumped from eastern Queens (by the Jamaica Water Supply Company, JWSC) to meet daily water-supply demands.
- A simulation describing the effects of a shutdown of pumping by the JWSC to allow ground-water levels to recover to a "full-reservoir" condition is presented. This "full reservoir" condition maintains ground-water levels as high as possible without flooding basements or other underground structures. Pumping required for dewatering is estimated in the analysis. This condition maximizes the volume of water stored in the ground-water system and the amount of ground water available for supplemental pumping.
- Simulations of supplemental pumping scenarios under the "full-reservoir" condition are presented. This condition affords significantly greater pumping rates and ground-water supplements than the previous stressed condition.



Base modified from U.S. Geological Survey, 1:100,000; Hydrography and cultural features modified to reflect the period from 1903 through 1936

Modified from Veatch and others, 1906

EXPLANATION

——50—— WATER TABLE CONTOUR Shows altitude of water table. Contour interval 5 and 10 feet. Datum is sea level

— — — — SOUTHERN EXTENT OF HARBOR HILL MORAINE

—··——········ ESTIMATED POSITION OF MAJOR GROUND-WATER-DIVIDE Dotted where approximately located

Figure 4. Water table in 1903. (Modified from Veatch and others, 1906)

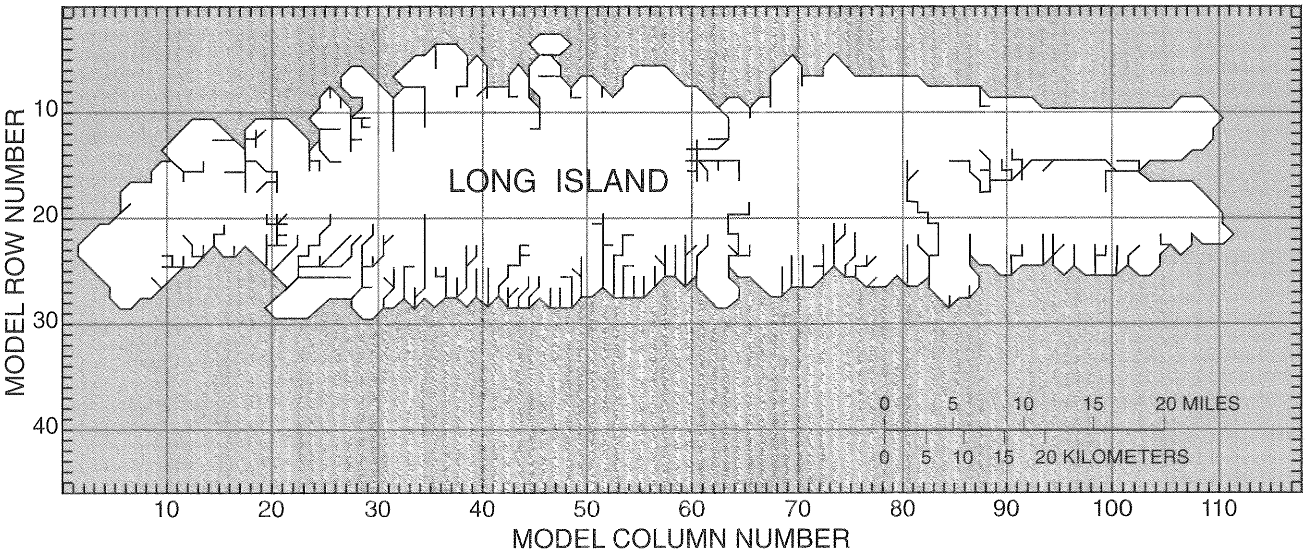


Figure 5. Grid of the Long Island ground-water flow model showing discrete stream and shore boundaries.

Model Design

The three-dimensional model of the Long Island ground-water flow system used in this investigation was developed to allow islandwide evaluation of natural and man-induced hydrologic effects. It represents the entire Long Island ground-water flow system to its natural hydrologic boundaries; simulations of hydrologic conditions on an islandwide scale were available as a starting point for this investigation. A complete description of the construction and calibration of this model is presented in Buxton and Smolensky (1999).

A model grid depicts the discrete representation of the stream and shoreline boundaries (fig. 5). Grid cells are 4,000 ft on a side; the grid has 46 rows and 118 columns. Shoreline- and subsea-discharge boundaries are represented by constant head. Stream boundaries are represented as head-dependent flow boundaries. The saltwater-freshwater interfaces within the confined aquifers (Jameco, Magothy, Lloyd) are represented as impermeable boundaries, as is the bottom (bedrock) boundary.

The vertical sequence of aquifers and confining units is represented in four layers that generally correspond to the four aquifers (fig. 6A and 6B). Where the confining units are present, the upper glacial aquifer is in model layer 1 (the uppermost), the Jameco and Magothy aquifers are in layers 2 and 3, and the Lloyd aquifer is in layer 4. The confining units are represented implicitly between model layers; the Gardiners Clay impedes vertical flow between model layers 1 and 2, and the Raritan confining unit impedes vertical flow between model layers 3 and 4.

The simulated predevelopment water table (fig. 7) closely matches the predevelopment water table estimated from observed data (fig. 4), including the north-to-south asymmetry, anomalous high-water levels along the northern shore, and gradients converging to stream channels.

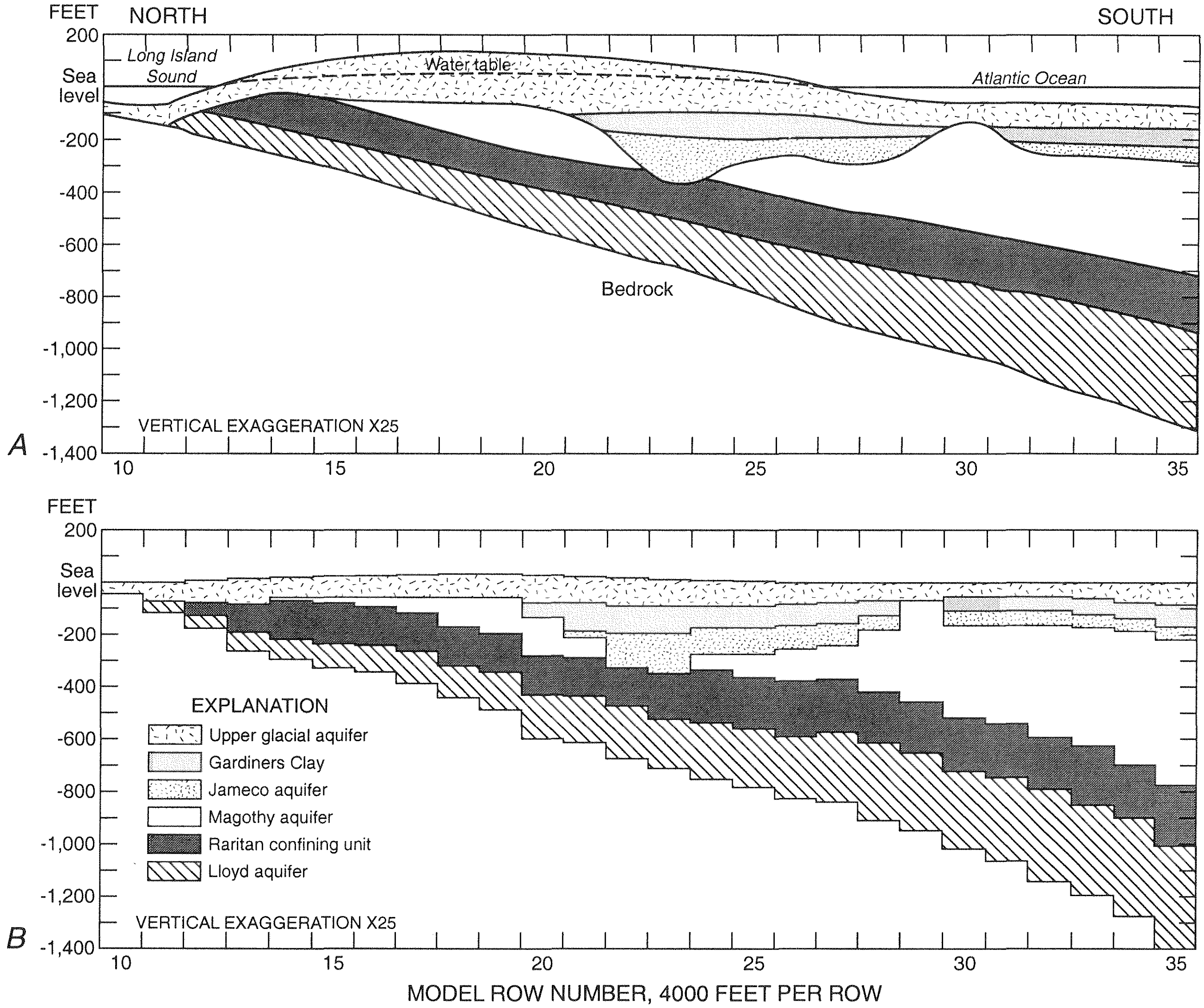


Figure 6. Cross-sectional representation of model layers in column 19. A, Hydrogeologic section. B, Discrete model representation. (The grid is shown in figure 5.)

Recent Stressed Hydrologic Condition

By 1975, about 93 percent of the land surface of Brooklyn and Queens is developed -- approximately 27 percent for vehicular use (paved roads, highways, parking lots), and 35 percent residential (New York City Department of Environmental Protection, 1979). Ground-water is pumped for industry, public supply, and dewatering. Paving over large areas of land surface has significantly decreased recharge from precipitation and increased runoff. A vast combined storm- and sanitary-sewer network diverts wastewaters to ocean outfall. Filling in of extensive wetlands near the shore and stream channels have changed the physical character of the island. Continuous leakage from a water-supply system that carries about 750 Mgal/d (more than 90 percent of which is imported from upstate surface-water sources) may contribute more than one third of the ground-water system budget.

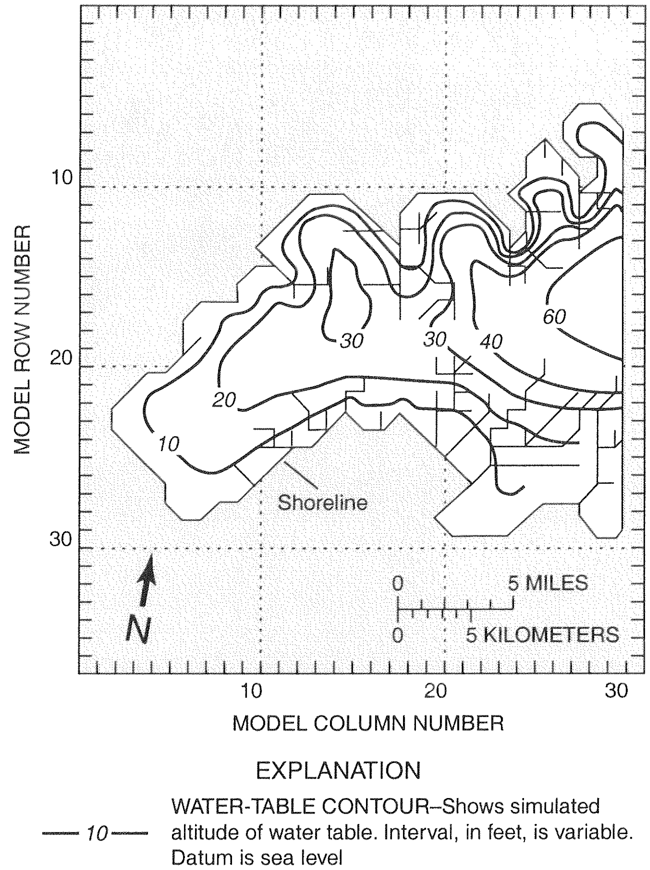


Figure 7. Simulated configuration of the predevelopment water table in western Long Island. (Modified from Buxton and Smolensky, 1999.)

In the early 1980's, the ground-water system of western Long Island was in a state of dynamic equilibrium. Despite natural fluctuations in recharge and changes in the location of pumping sites, the total stress on the ground-water system was relatively constant, as were ground-water levels. This recent period of hydrologic equilibrium was simulated during calibration of the islandwide ground-water model and is described in Buxton and Smolensky (1999).

Water levels in the upper glacial (water-table) aquifer are high along the northern shore where low permeability moraine deposits persist (fig. 8A). The water table increases to the east where it attains its highest altitude in central Nassau County. Water levels in the Jameco-Magothy aquifer mimic the water table in the north and east where the absence of the Gardiners Clay permits good hydraulic connection between these aquifers (fig.8B). Water levels in the Lloyd aquifer are considerably different because of confinement by the Raritan confining unit. Cones of depression from public-supply pumping of the JWSC are evident in the water levels of all three aquifers (fig. 8). An additional, small cone of depression in the Lloyd aquifer in southwestern Nassau is caused by pumping in Long Beach (fig. 1), a barrier island community that has no shallow source of supply.

The JWSC pumps approximately 61 Mgal/d, of which about 23 percent is from the upper glacial aquifer; 67 percent is from the Jameco-Magothy aquifer; and only 10 percent is from the Lloyd aquifer. Despite less pumping

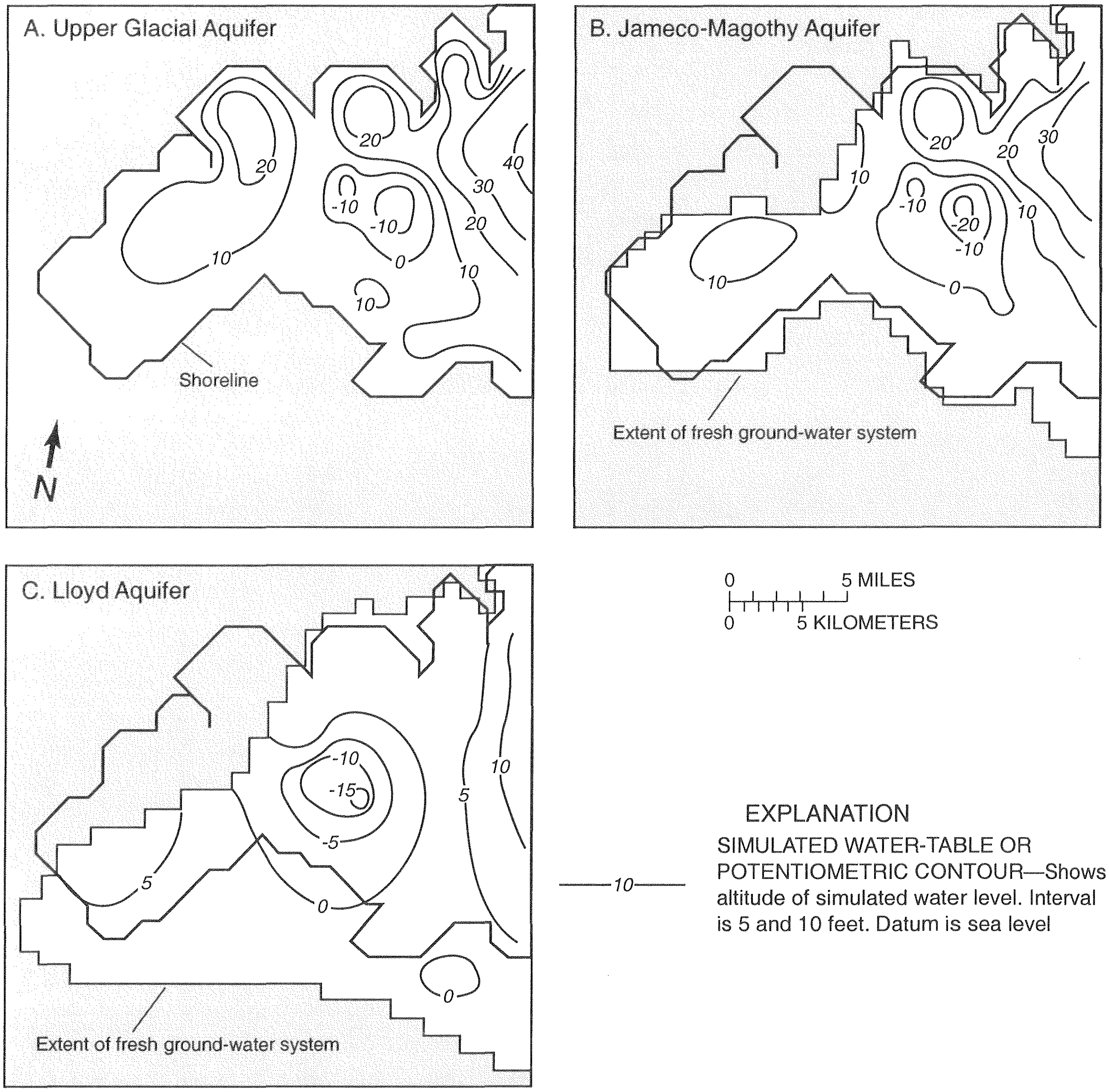


Figure 8. Simulated ground-water levels under recent stressed conditions. A, The upper glacial (water-table) aquifer, model layer 1. B, The Jameco-Magothy aquifer, model layer 3. C, The Lloyd aquifer, model layer 4.

from the Lloyd aquifer, its cone of depression is the most severe for two reasons--(1) this aquifer is confined by the Raritan confining unit throughout most of western Long Island (requiring significant vertical gradients to move water down to it), and (2) ground-water levels are drawn down simultaneously in the overlying aquifers; therefore, to increase downward flow to wells in this aquifer, water levels must be depressed even lower than levels in the overlying aquifer.

Simulated conditions presented in figure 8 define the initial conditions for predictive simulations of ground-water supplements under recent stressed conditions. Comparisons with observed water-level data are available in Buxton and Smolensky (1999).

Table 2. Comparison of the ground-water budget of western Long Island from model simulations of predevelopment and recent stressed conditions. [From Buxton and Smolensky (1999)]

Budget component	Predevelopment conditions	Present conditions
Inflow:		
Recharge from precipitation	160	78
Leakage from water-supply lines and other infiltration	--	58
Ground water from Nassau County	4	11
Total	164	147
Outflow:		
Stream base flow	58	12
Pumping:		
- Public supply (net)	--	61
- Private (net)	--	16
Subsea discharge	106	58
Total	164	147

Under this condition, recharge from precipitation has been reduced from predevelopment levels by 51 percent, to only 78 Mgal/d (table 2). The loss in recharge is largely replaced, however, by infiltration of an estimated 58 Mgal/d from leaking water-supply lines, leaking sewer lines, and lawn watering. Also, drawdown from pumping has increased the amount of ground water flowing into Queens from Nassau County (from 4 to 11 Mgal/d). Ground water pumping of about 77 Mgal/d (net) is a major component of discharge from the system. Most stream channels have all but dried up; base flow and subsea discharge have decreased to about 20 percent and 55 percent of predevelopment rates, respectively.

The interface between fresh and salty ground water in the Jameco-Magothy and Lloyd aquifers is identified in section and plan view on figures 3, 8B, and 8C. The interface slopes landward with increasing depth. At equilibrium, the interface is stable, balanced by equal pressures in the salty and fresh ground water. However, observed heads in the Jameco-Magothy and Lloyd aquifers are not sufficient to balance the pressure of static seawater; hydraulic heads of 7.5 to 15 ft would be needed in the Jameco-Magothy aquifer, and hydraulic heads of 15 to 30 ft would be needed in the Lloyd aquifer. Thus, the saltwater-freshwater interface is migrating landward at a slow rate. Applying Darcy's law, Buxton and Shernoff (1995) estimated the rate of movement to be from 0.5 to 1.0 ft/d in the Jameco-Magothy aquifer, and less than 0.1 ft/d (35 feet per year) in the Lloyd aquifer. These rates of landward movement of the saltwater-freshwater interface may seem slow, but, at a landward rate of 1.0 ft/d, the interface would migrate approximately 1 mile in 15 years. This movement is of major concern to long-rang resource management, especially because saltwater intrusion could be more rapid near pumping wells or in local zones that have high permeability or low porosity.

Ground-Water Supplements Under Recent Stressed Conditions

The steady-state simulation of recent (early 1980's) stressed conditions was used as the basis for simulations of the various supplemental withdrawal scenarios presented in this section. Transient-state simulations of pumping 50, 100, and 150 Mgal/d from the ground-water system were made. The maximum allowable duration for each pumping rate was determined by when simulated ground-water levels reached sea level. This is a relatively arbitrary determination because the simulated water level is related to the cell size and represents an average in the cell, and the duration is approximated at the nearest discrete timestep. However, this determination provides a consistent basis for comparison of various scenarios and avoids adverse effects of excessive drawdown. The recovery time (that is, the length of time before the system could again be used as a supplemental source of water supply) was estimated by cessation of pumping after the appropriate duration and observing system recovery. Recovery was considered sufficient when water levels attained 90 percent of their prepumping levels. Recovery times were estimated from simulations of natural recovery and when recovery was accelerated by means of artificial recharge using surplus surface water.

The number and the location of pumping centers (fig. 9) were determined initially from a preliminary review of selected geographic, hydrologic, and water-quality criteria and refined by trial-and-error testing. The distribution of pumping centers probably could be improved after a detailed analysis and consideration of additional engineering-design criteria, but that was beyond the scope of this study. Existing wells were inventoried to indicate well requirements to achieve pumping rates in the simulated pumping scenarios. Approximately 30 wells owned by the JWSC in southeastern Queens produce an average of 61 Mgal/d with the largest wells yielding more than 2.0 Mgal/d (JWSC, written commun., 1986). In these simulations, therefore, pumping was distributed among 50 centers. Each center in the 50-Mgal/d simulation would pump 1 Mgal/d, each center in the 100-Mgal/d simulation would pump 2 Mgal/d, and each center in the 150-Mgal/d simulation would pump 3 Mgal/d. Wells were located such that they are:

1. Away from areas already severely affected by JWSC pumping;
2. concentrated in areas of high transmissivity and in unconfined aquifers, where drawdown would propagate more slowly;
3. In the central areas of the island (distant from shore and subsea discharge boundaries) to maximize the amount of water derived from storage before drawdown reaches the system boundaries; and
4. Near large-diameter conduits in the water-supply infrastructure to enable the pumped water to be added easily to the supply system (New York City Department of Environmental Protection, 1979).

Ground-water quality is an additional consideration for well-location. However, according to available water-quality data (Buxton and Shernoff, 1995, and Stern and Todd, 1984), the potable quality of significant volumes of pumped ground water cannot be assured. Therefore, it is assumed in this analysis that the pumped water may require treatment to assure acceptable quality.

The upper glacial aquifer has 33 pumping centers (fig. 9A), 21 of which tap outwash deposits; only 12 tap moraine deposits, where

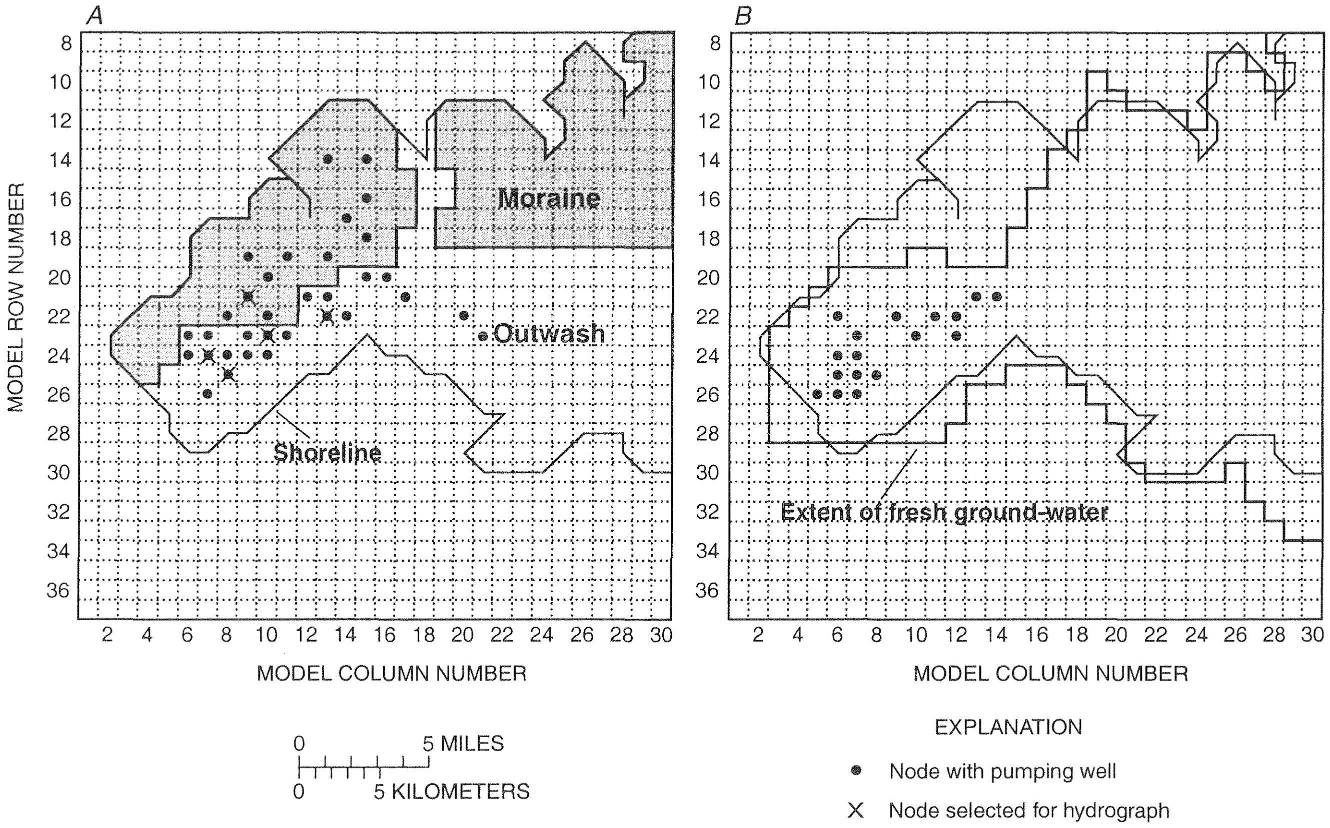


Figure 9. Location of pumping centers used for pumping scenarios under recent stressed conditions. A, The upper glacial aquifer, model layer 1 (33 centers). B, The Jameco-Magothy aquifer, model layer 3 (17 centers).

hydraulic conductivity is considerably lower. The Jameco-Magothy aquifer contains 17 centers (fig. 9B), which are screened at the base of the Jameco-Magothy aquifer unit (in model layer 3). After excessive drawdown from testing only 1 of the 50 pumping centers screened in the Lloyd, the aquifer was considered too sensitive to be utilized as a source.

Pumping Supplements

Hydrographs of the average predicted drawdown among five representative model cells in the upper glacial aquifer in response to pumping rates of 50, 100, and150 Mgal/d are shown in figure 10. The rate of drawdown increases with the rate of pumping. The pumping duration is defined as the time required to decrease the average ground-water level in the five representative cells to near sea level. The duration for 50 Mgal/d was 15 months; for 100 Mgal/d, 5.7 months; and for 150 Mgal/d, 3.1 months (table 3).

The distribution of hydraulic head in each aquifer for the 17.3 billion-gallon (100 Mgal/d for 5.7 months) pumping scenario demonstrates the distribution of drawdown from pumping (fig. 11); the head distributions for the other pumping scenarios are similar and are not presented. Most of the drawdown is concentrated in Brooklyn near the pumping centers and does not exacerbate the existing cone of depression in Queens (compare with initial head distribution, fig. 8). Water levels in Brooklyn are drawn down slightly below sea level in small areas inland away from the shore and the saltwater-freshwater interface. Despite the absence of pumping from the Lloyd aquifer, some drawdown propagates into this aquifer from the overlying aquifers.

Pumping 50 Mgal/d for 15 months yielded the largest total volume of ground water, 22.8 billion gal (table 3), and pumping 150 Mgal/d for 3.1 months yielded the least, 14.1 billion gal. Pumping at the lower rate produced a cone of depression with a larger volume and resulted in more water being drained from storage and diverted from the boundaries before water levels declined to sea level. At cessation of pumping for the 50-Mgal/d supplement, 18.7 billion gal of the water (or 82 percent of that pumped) was derived from storage. However, at cessation of pumping for the 150-Mgal/d supplement, 13.5 billion gal of the water (or 96 percent of that pumped) was derived from storage.

Natural Recovery

The hydrographs in figure 10 show that the rate of natural recovery slows rapidly and waiting for full (100 percent) recovery is impractical. The time required for 90-percent recovery after the cessation of pumping ranges from 4.8 to 5.6 years (fig. 10 and table 3). The recovery time after pumping 50 Mgal/d for 15 months is longest because that simulation removed the largest volume of water from storage. The distribution of hydraulic head in the system's three aquifers at 90-percent recovery have a configuration similar to that in the initial condition (fig. 8); water levels near the center of the pumping in Brooklyn show drawdown of only a few feet.

Acceleration of Recovery by Artificial Recharge

The effect of using artificial recharge to accelerate recovery was demonstrated by additional simulations. Surplus surface water from the upstate reservoir system are available during brief periods of reservoir surplus. Andrew Warren (O'Brien and Gere Engineers, Inc., written commun., 1986) estimated that, during an average year, the upstate reservoir system could provide 100 Mgal/d for 60 days from mid-March to mid-May.

Artificial recharge by means of diversion of storm runoff to excavated recharge basins

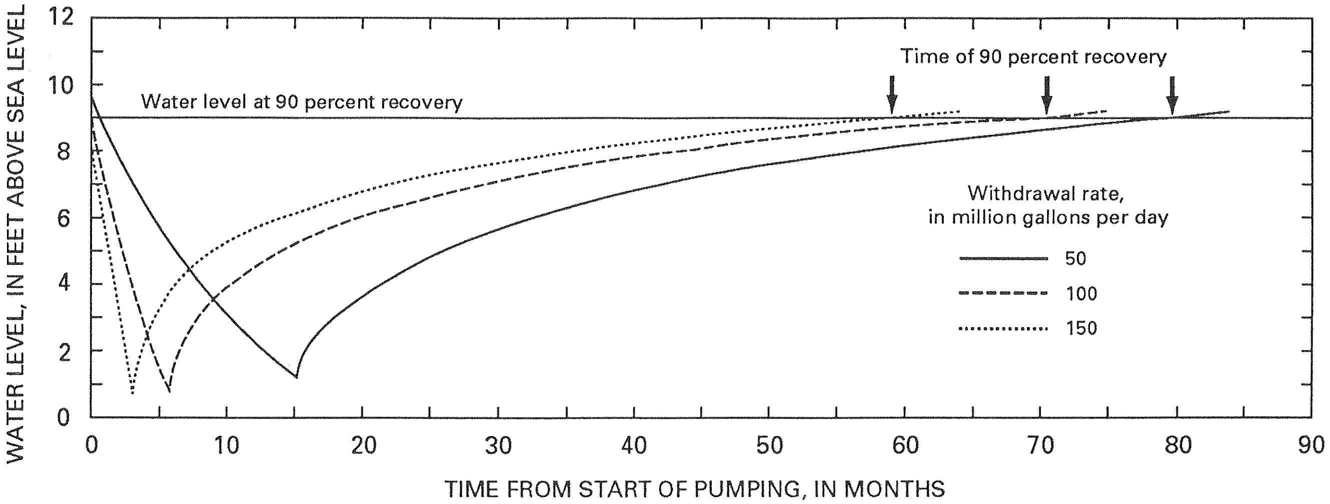


Figure 10. Average simulated head among five representative model cells during short-term pumping at rates of 50, 100, and 150 million gallons per day with natural recovery. (The location of pumping centers is shown in figure 9.)

Table 3. Characteristics of short-term ground-water pumping under recent stressed conditions.

Pumping rate (million gallons per day)	Maximum allowed duration (months)	Total volume pumped (billion gallons)	Time required for 90-percent recovery: Natural recharge (years)	Time required for 90-percent recovery: Artificial recharge (months)	Maximum decrease in boundary discharge (million gallons per day)
50	15.0	22.8	5.6	16.5	15.6
100	5.7	17.3	5.3	14.3	12.8
150	3.1	14.1	4.8	16.9	10.5

has been used successfully for many decades in Nassau and Suffolk Counties to maintain natural rates of recharge from precipitation (Ku and Simmons, 1986). Sustainable infiltration rates of 1 ft/hr (foot per hour) are common in the sand outwash plain of southern Nassau and Suffolk Counties (H.F.H. Ku, U.S. Geological Survey, oral commun., 1988); similar infiltration characteristics are expected in the outwash deposits of southern Queens and southeastern Brooklyn.

A total area of approximately 13 acres was assumed necessary to recharge the ground-water system at an infiltration rate of 1 ft/hr. The recharge was distributed to model nodes that represent the locations of 21 hypothetical recharge basins that would be close to the pumping centers (fig. 12).

Ground-water pumping was assumed to occur in September or October, the time of year at which a drought warning was issued during a major drought in 1981. Surplus surface water for recharge was assumed to be unavailable until at least 18 months after the start of ground-water pumping to allow surface-water reservoirs time to recover. Hydrographs of the ground-water levels through drawdown and recovery using artificial recharge (fig. 13) show an initial period of rapid drawdown during pumping, then a period of natural recovery until surface water is available for artificial recharge. During recharge, water levels near the basins recovered rapidly as local water-table mounds form under the basins. After recharge stops, ground-water levels near the basins recede as the mounds dissipate. Ground-water levels remain above the 90-percent recovery point for two of the three scenarios; the large volume of water drained from storage in the 50-Mgal/d simulation prevented the ground-water system from achieving 90-percent recovery until after an additional month of recharge the following year. The exact time required for 90-percent recovery is difficult to define; the times from the end of pumping until the end of artificial recharge required for 90-percent recovery are given in table 3. Model results indicate that the use of artificial recharge to increase recovery would have a marked effect on recovery times. These decreased from 5 or 6 years to less than 18 months.

Source of Water to Pumping

The cumulative volume of water pumped and the sources of water for the 100-Mgal/d pumping rate are shown in figure 14A. Initially, water is derived solely from storage. When the drawdown reaches the system's natural-discharge boundaries (streams or the shoreline), it diverts water from these boundaries toward the pumping well, reducing ground-water seepage to streams (base flow) and discharge to the shoreline and subsea boundaries (which holds back saltwater intrusion).

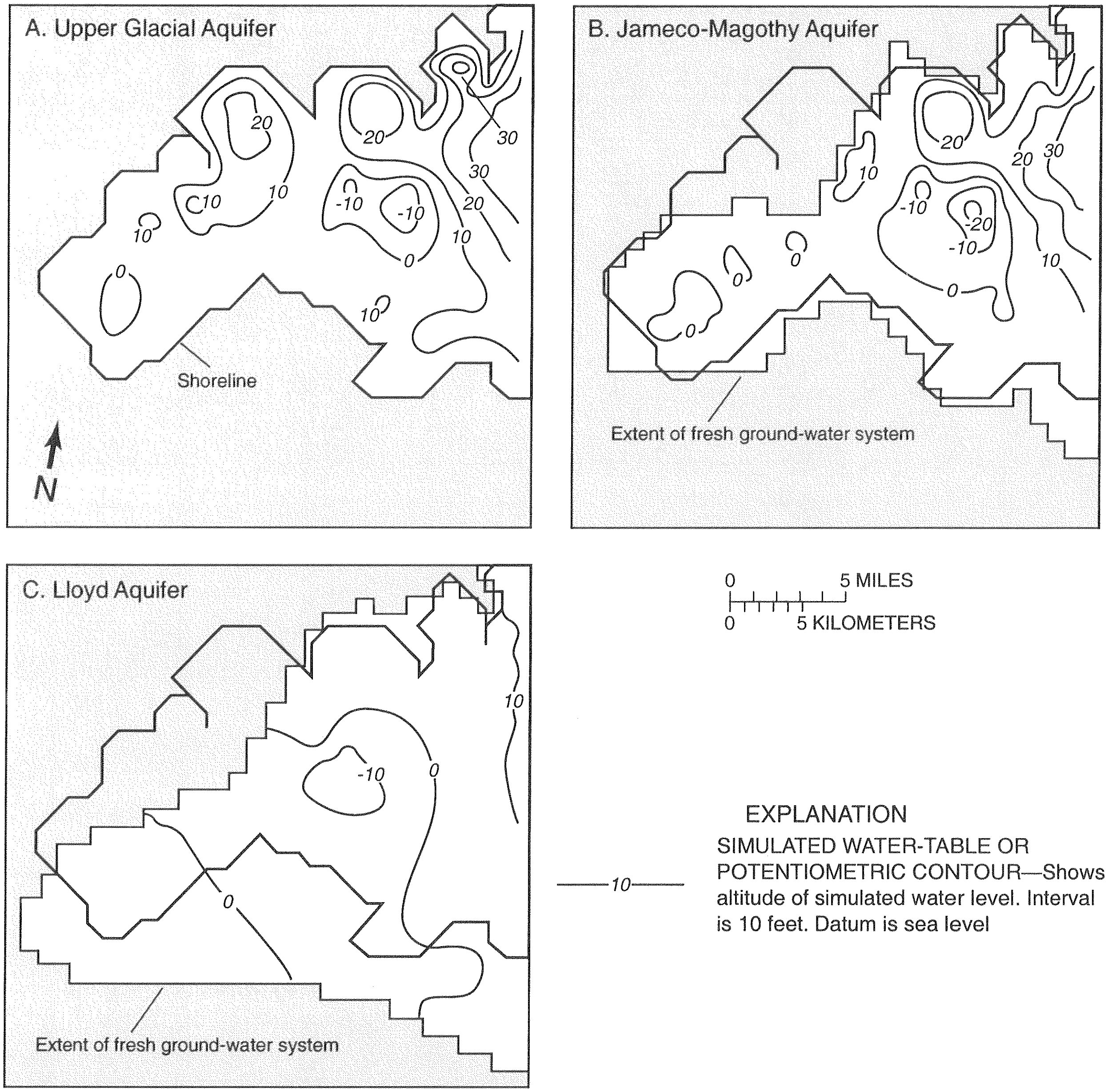


Figure 11. Distribution of hydraulic head in western Long Island after pumping 100 million gallons per day for 5.7 months. A, The upper glacial (water-table) aquifer, model layer 1. B, The Jameco-Magothy aquifer, model layer 3. C, The Lloyd aquifer, model layer 4.

At cessation of pumping (5.7 months), only a small fraction of the total volume pumped represents a decrease in boundary discharge (5 percent) (fig. 14A). After cessation of pumping, water levels recover and water is returned to storage. Throughout the period, the cumulative volume of water pumped is equal to the net amount derived from storage plus the amount derived from decreased boundary discharge. Ultimately, all storage is replenished; the original equilibrium condition is again reached; and the total volume of water pumped represents the total decrease in boundary flow during the period of pumping and recovery.

The decrease in the rate of boundary discharge changes through the pumping and recovery period (fig. 14B). After drawdown

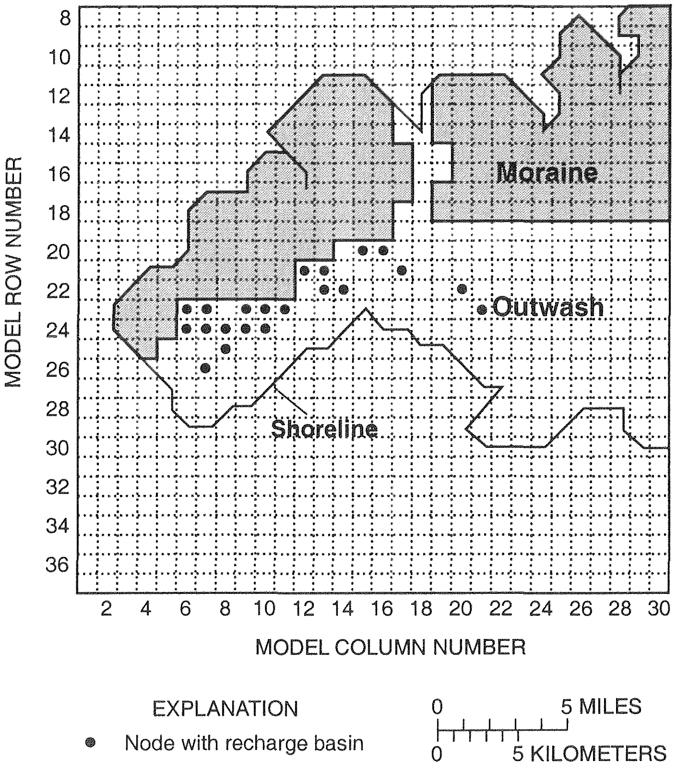


Figure 12. Locations of recharge basins used to accelerate recovery of ground-water levels after pumping under recent stressed conditions.

reaches the boundary, boundary discharge decreases consistently. After cessation of pumping, water-level recovery eventually reaches the system boundaries, and the decrease in the rate of boundary discharge decreases. The maximum decrease in boundary discharge is 12.8 Mgal/d (only 13 percent of the pumping rate); it occurs about 130 days after the pumping stopped. The loss of boundary discharge is dispersed over the entire 5.8-year period of pumping and recovery. The area under the curve in figure 14B is the total volume of water derived from boundary discharge and, if extended to steady-state, would yield the total volume of ground water pumped.

The maximum decrease in boundary discharge for the 50- and 150-Mgal/d simulations are 15.6 and 10.5 Mgal/d, respectively (table 3). The longer the pumping duration, the closer the system gets to equilibrium, and the larger the maximum decrease in boundary discharge relative to the pumping rate.

The effect of accelerating recovery by artificial recharge on the cumulative volume of water removed from storage and boundary flow for the 100-Mgal/d pumping scenario is shown in figure 15A. Initially, the recharge (considered an injection that reduces net pumping) replenishes ground-water storage. However, as recovery of water levels continues, the reduction in boundary discharge is mitigated (compare fig. 14A, 15A). The total volume of water lost as boundary discharge, assuming a return to equilibrium, is equal to the volume of water pumped less the volume returned by artificial recharge. Artificial recharge affects neither the maximum decrease in boundary discharge nor the time at which it occurs, but does decrease the total volume of water diverted from boundary discharge (compare figs. 14B, 15B).

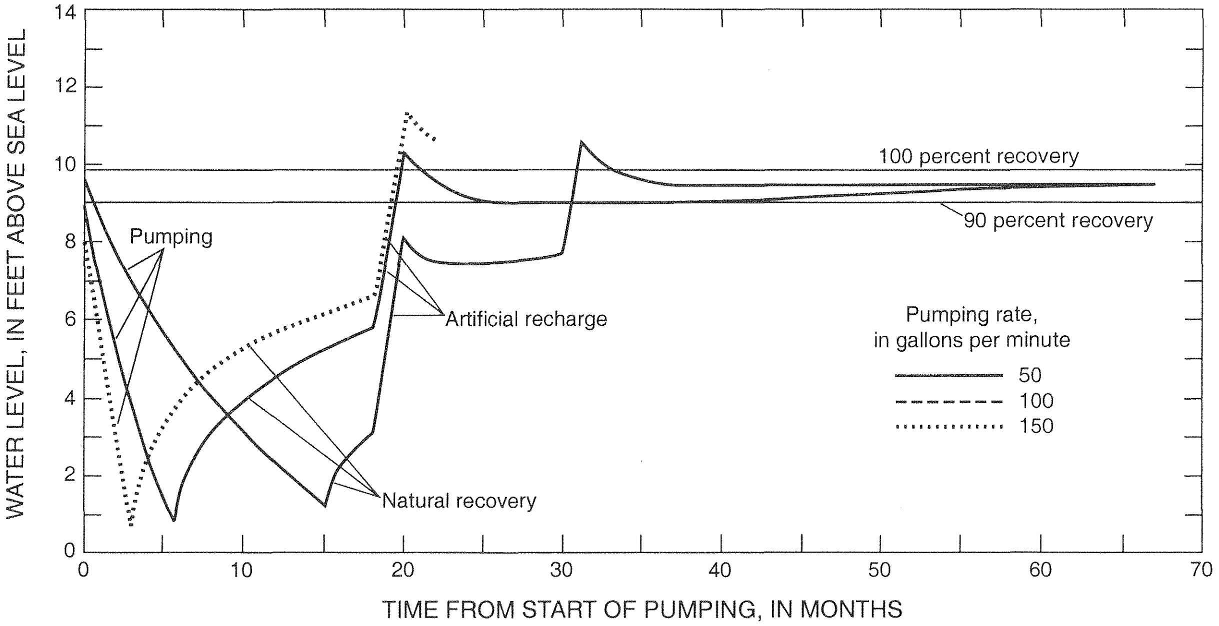


Figure 13. Average simulated head among five representative model cells during short-term pumping at 50, 100, 150 million gallons per day with recovery accelerated by artificial recharge. (Representative cells are shown in figure 9.)

"Full-Reservoir" Hydrologic Condition

Supplemental pumping scenarios under the recent stressed condition are limited because of the pumping of JWSC in southeastern Queens, which makes additional pumping in that area impractical. This section discusses the possibility of replacing public-supply pumping by the JWSC with surface water, allowing the ground-water system to recover and add a considerable volume of water to ground-water storage. The resulting "full-reservoir" condition approximates the maximum ground-water levels that could be allowed without causing land-surface or subsurface-structure flooding, and maximizes the potential use of ground water as a periodic supplement. Two model simulations are presented--one assesses ground-water recovery after cessation of JWSC pumping and the other includes the pumping necessary to prevent flooding of basements and other underground structures and defines the "full-reservoir" condition.

Cessation of Public-Supply Pumping

Cessation of all existing pumping in Brooklyn and Queens will not return the ground-water system to predevelopment conditions because of significant other effects of development. The simulated water-table configuration arising from cessation of the 61 Mgal/d pumped by JWSC (fig. 16) indicates that the water table recovers more than 40 ft in eastern Queens. Although not shown, a proportional recovery occurs in the Jameco-Magothy and the Lloyd aquifers. The simulation indicates that at least an additional 35 Mgal/d of ground water would discharge to the stream channels that remain in Queens and southwestern Nassau County, and an additional 27 Mgal/d would discharge to nearby salty ground- and surface-water bodies. In some areas, ground-water levels would intersect land surface, indicating basement flooding and/or redevelopment of springs and wetlands that have been dry for most of this century.

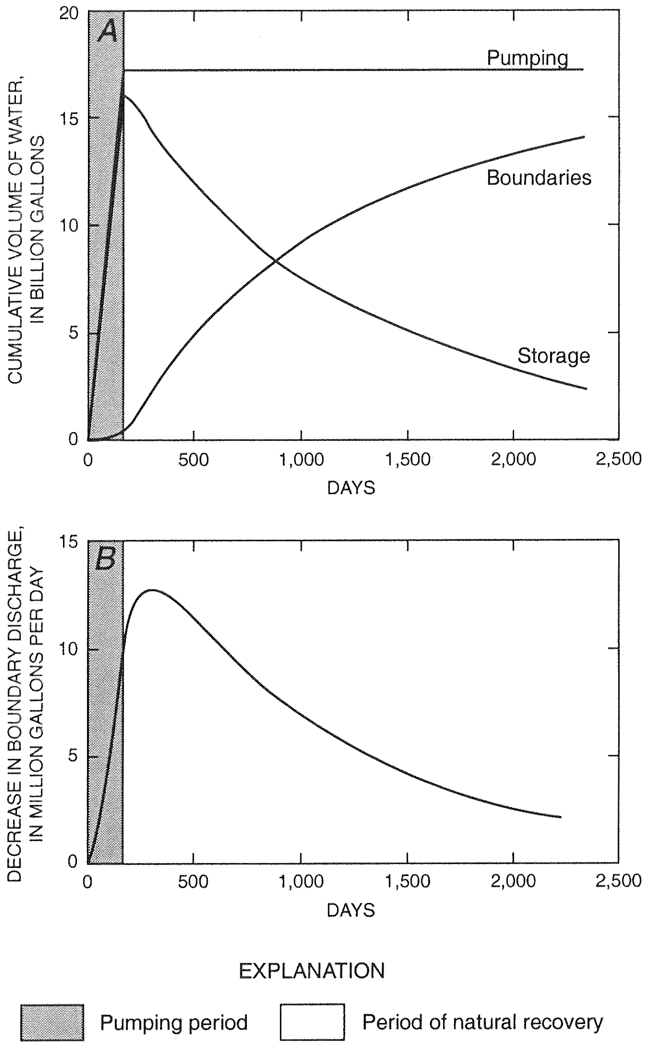


Figure 14. Ground-water budget during 5.7 months of pumping at 100 million gallons per day with natural recovery. A, Cumulative volume of water derived from storage and discharge boundaries. B, Decrease in rate of boundary discharge.

Evaluation of Required Dewatering

Prevention of basement flooding by elevated ground-water levels would require continual pumping to maintain drawdown in susceptible areas. Several simulations were run to estimate the amount and the distribution of pumping that would alleviate flooding. The best simulation indicated that pumping of approximately 19 Mgal/d from shallow wells distributed through flood-prone areas would maintain the water table at a high, but safe, level; that is about 10 feet below land surface (fig. 17). The water levels shown in figure 17 still are significantly above present levels (see fig. 8), which indicate that considerably more water is available in storage. The water table has risen from more than 10 ft below sea level to 30 ft above sea level; maximum water-level recovery in the Jameco-Magothy aquifer is from 20 ft below sea level to nearly 30 ft above sea level, and water levels in the Lloyd aquifer, which were below sea level throughout a major part of Queens County, are now near or more than 10 ft above sea level.

Simulation results indicate that the reduction of pumping from 61 Mgal/d for public supply to 19 Mgal/d in flood-prone areas would produce a 24-Mgal/d increase in discharge to streams and an 18-Mgal/d increase in discharge to surrounding salty ground- and surface-water bodies. In addition, the increased hydraulic head at the saltwater-freshwater interface along southern Long Island would reduce the rate of landward migration of the saltwater interface. The reduction in pumping also would cause considerable recovery of ground-water levels in southwestern Nassau County, where water levels and streams have been severely lowered by intense urbanization and ground-water development.

Ground-Water Supplements Under "Full-Reservoir" Conditions

The potential for use of ground water as a supplemental source of public supply under the "full-reservoir" condition was evaluated through simulation of pumping scenarios at rates of 200, 300, and 400 Mgal/d. The model simulation of the "full-reservoir" condition, described in the previous section, was used as the initial condition. The number of pumping centers was increased to 100 and dispersed throughout Brooklyn and Queens using the same criteria as for pumping cen-

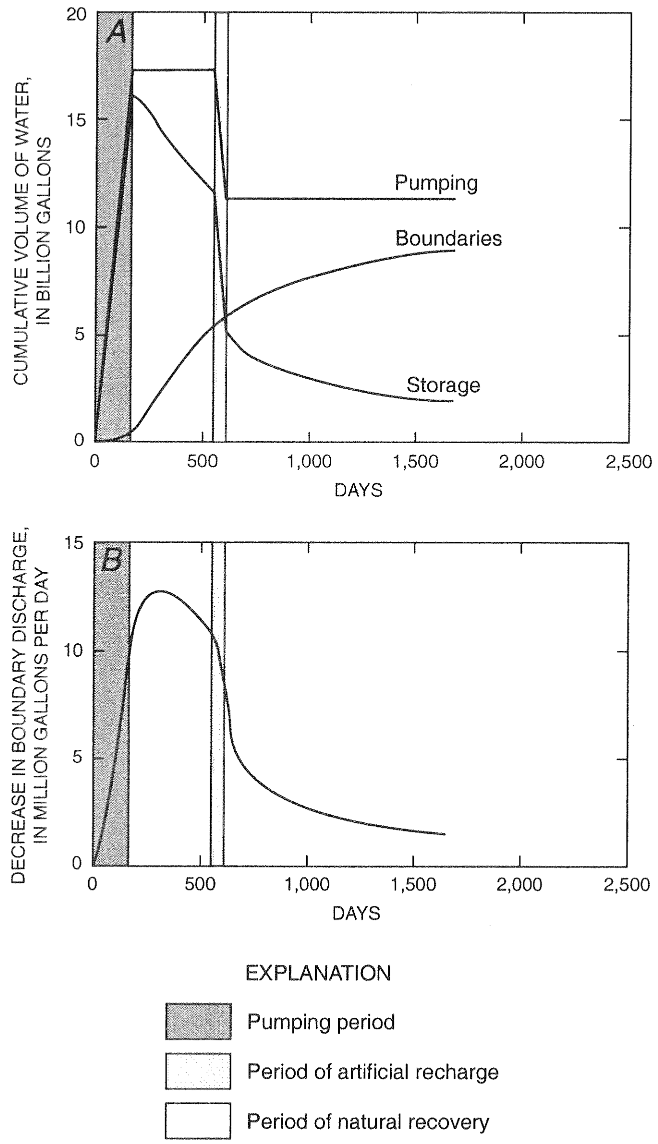


Figure 15. Ground-water budget during 5.7 months of pumping at 100 million gallons per day with recovery accelerated by artificial recharge. A, Cumulative volumes of water derived from storage and discharge boundaries. B, Decrease in rate of boundary discharge.

ters under the previous analysis. Each of the 100 pumping centers would pump 2, 3, or 4 Mgal/d for the 200-, 300-, and 400-Mgal/d simulations, respectively. Again issues related to well-field design at each pumping center are not addressed.

Several transient-state simulations were run to estimate the optimum distribution of pumping centers both across the area and within the upper glacial and the Jameco-Magothy aquifers. The resulting distribution of pumping is shown in figure 18; 68 pumping centers tap the upper glacial aquifer (model layer 1), 20 of which are in moraine deposits and 48 are in outwash deposits; 32 tap the base of the Jameco-Magothy aquifer (model layer 3). The greatest density of pumping is in central Queens, where initial water levels are highest and the aquifers thickest.

Pumping Supplements

The average simulated water level among ten representative model cells (located on figure 18) during pumping of the 200, 300, and 400 Mgal/d supplements is plotted in figure 19. As in the recent stressed conditions analysis, pumping was stopped when the water table was drawn down to near sea level. The duration for pumping 200 Mgal/d was 10.6 months, for 300 Mgal/d, 5.2 months; and for 400 Mgal/d, 3.1 months (table 4).

The distribution of hydraulic head in the three major aquifers after pumping at a rate of 300 Mgal/d for a duration of 5.2 months (figure 20) indicates that water levels in the water-table and the Jameco-Magothy aquifers are depressed slightly below sea level in local areas. Additional redistribution of pumping from the Jameco-Magothy aquifer to the water-table aquifer may improve the dispersal of drawdown throughout these aquifers. The head distribution for the 200 and 400-Mgal/d pumping scenarios were similar to that for the 300-Mgal/d simulation and are not shown.

Pumping 200 Mgal/d for 10.6 months yielded the largest total volume of ground water, 64.5 billion gal; pumping 400 Mgal/d for 3.1 months yielded the least, 37.2 billion gal (table 4). As observed in the analysis of recent stressed conditions, pumping at the lower rate allowed for a longer pumping duration and caused a cone of depression that has a greater volume. This is evident through

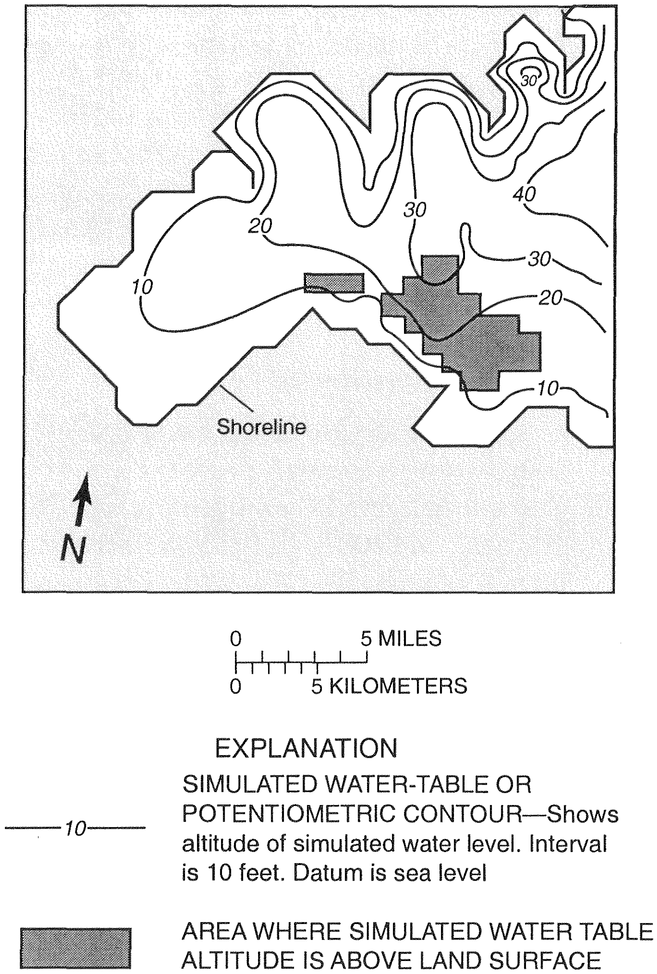


Figure 16. Simulated steady-state water-table configuration after cessation of pumping 61 million gallons per day by the Jamaica Water Supply Company.

comparison of the volume of water drained from storage at shutdown of pumping; pumping 200 Mgal/d withdrew 57.7 billion gal of water from storage (89 percent of the total volume of water pumped), whereas pumping 400 Mgal/d withdrew 35.8 billion gal from storage (96 percent of the total volume of water pumped).

Natural Recovery

The hydrographs in figure 19 show that although water levels began to recover immediately upon cessation of pumping, the times required for 90-percent recovery ranged from 4.7 years for the 400-Mgal/d simulations to 6.3 years for the 200-Mgal/d simulation (table 4). The longer recovery time for the 200-Mgal/d pumping scenario is consistent with the fact that it requires a larger volume of water to be returned to storage. Recovery times for the "full reservoir" condition are not significantly longer than those for the recent stressed conditions.

Acceleration of Recovery by Artificial Recharge

Acceleration of recovery using artificial recharge was estimated by applying the 100-Mgal/d surface-water surplus available subsequent to the drought through a network of 32 recharge basins (fig. 21). Again, pumping for supplemental ground water was assumed to begin in September or October (the time at which a drought warning was issued during a major drought in 1981). Recharge began about 18 months after the start of pumping allowing the surface-water reservoirs to recover from the drought and continued from mid-March through mid-May. Hydrographs of the simulated changes in ground-water levels through pumping and recovery are shown in figure 22.

After the cessation of pumping, ground-water levels recover naturally until the first episode of artificial recharge. During recharge, water levels recover rapidly, and ground-water mounds form under the basins. When recharge stops, water levels decline slightly as the mounds decrease. The effect of artificial recharge on recovery is evident through comparison of these hydrographs (fig. 22) with those for natural recovery (fig. 19). The 300- and 400-Mgal/d simulations require two recharge episodes, after which ground-water levels remain above 90-percent recovery. Recovery times after cessation of pumping at 300 and 400 Mgal/d are 26.8 and 28.9 months, respectively; their times are considerably shorter than those for

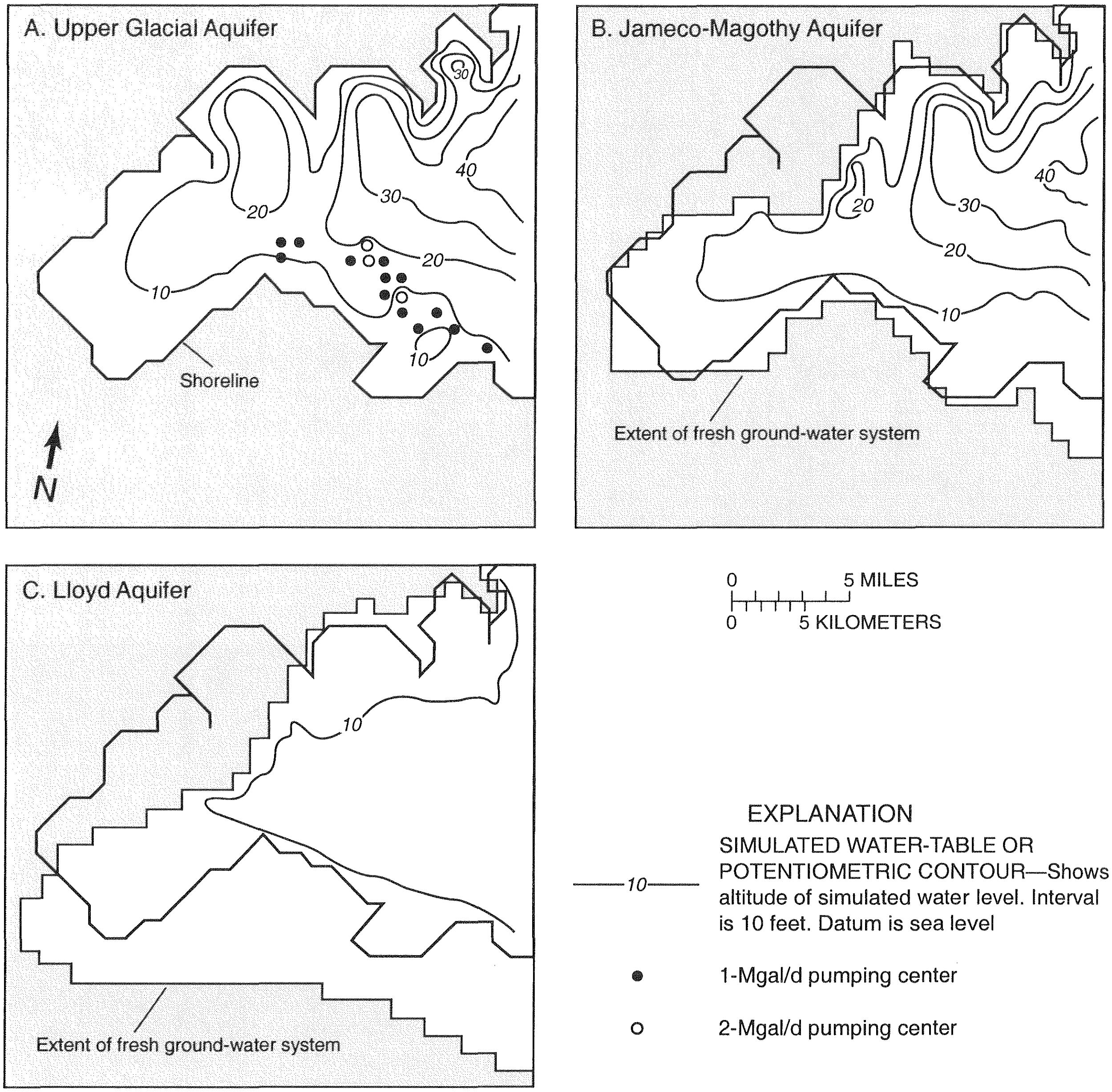


Figure 17. Simulated head distribution for the "full-reservoir" condition. A, The upper glacial (water-table) aquifer, model layer 1. B, The Jameco-Magothy aquifer, model layer 3. C, The Lloyd aquifer, model layer 4.

natural recovery (table 4). The 200-Mgal/d simulation requires a third recharge episode to bring water levels to above the 90-percent recovery level, probably because far more water is removed from storage during this pumping scenario (table 4).

Source of Water to Pumping

An analysis of the sources of water removed by pumping at 300 Mgal/d gave similar results to those for the previous analysis. The cumulative volume of water pumped in the 300-Mgal/d simulation is plotted along with the cumulative volume removed from storage and from system boundaries in figure 23A. Initially, all water pumped is derived from storage.

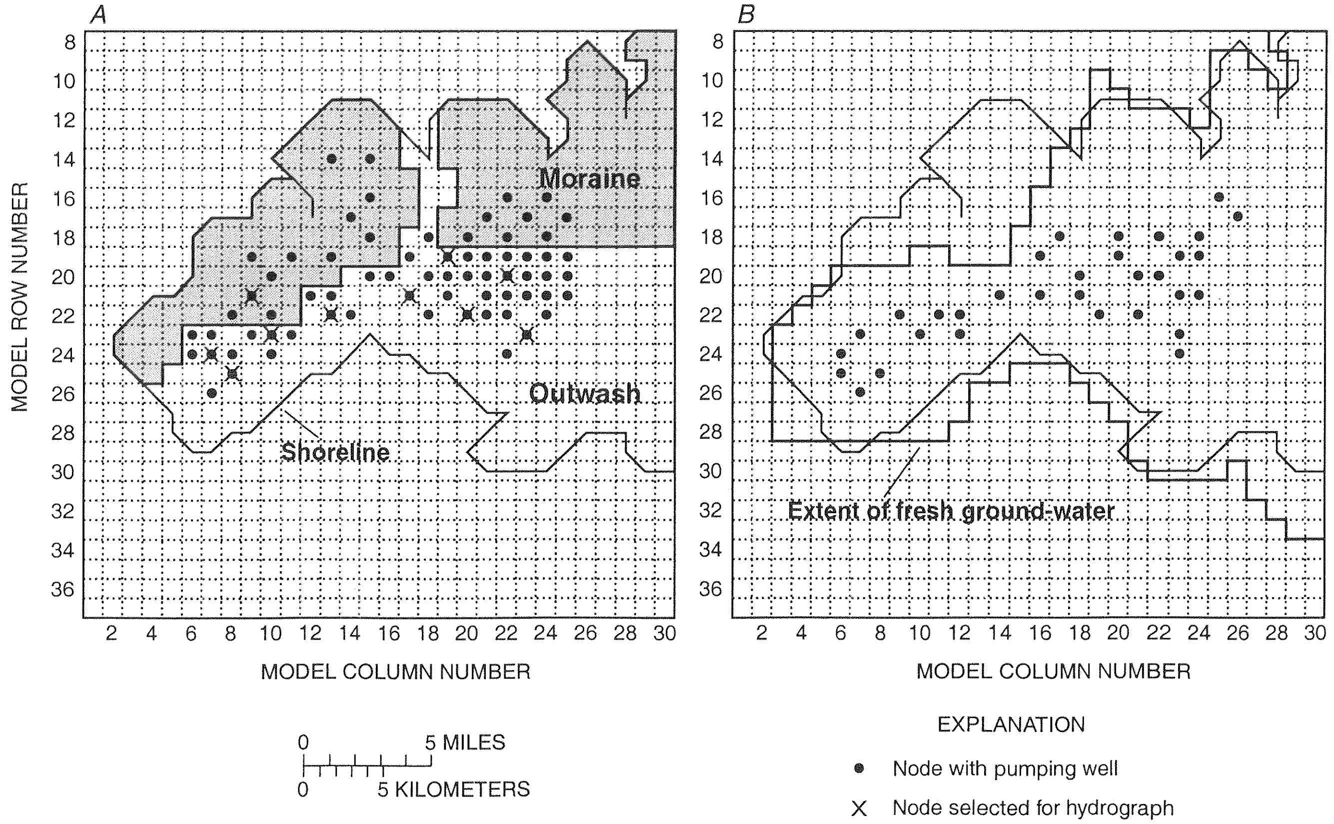


Figure 18. Location of pumping centers used for pumping scenarios under "full-reservoir" conditions. A, In the upper glacial aquifer, model layer 1 (68 centers). B, In the Jameco-Magothy aquifer, model layer 3 (32 centers).

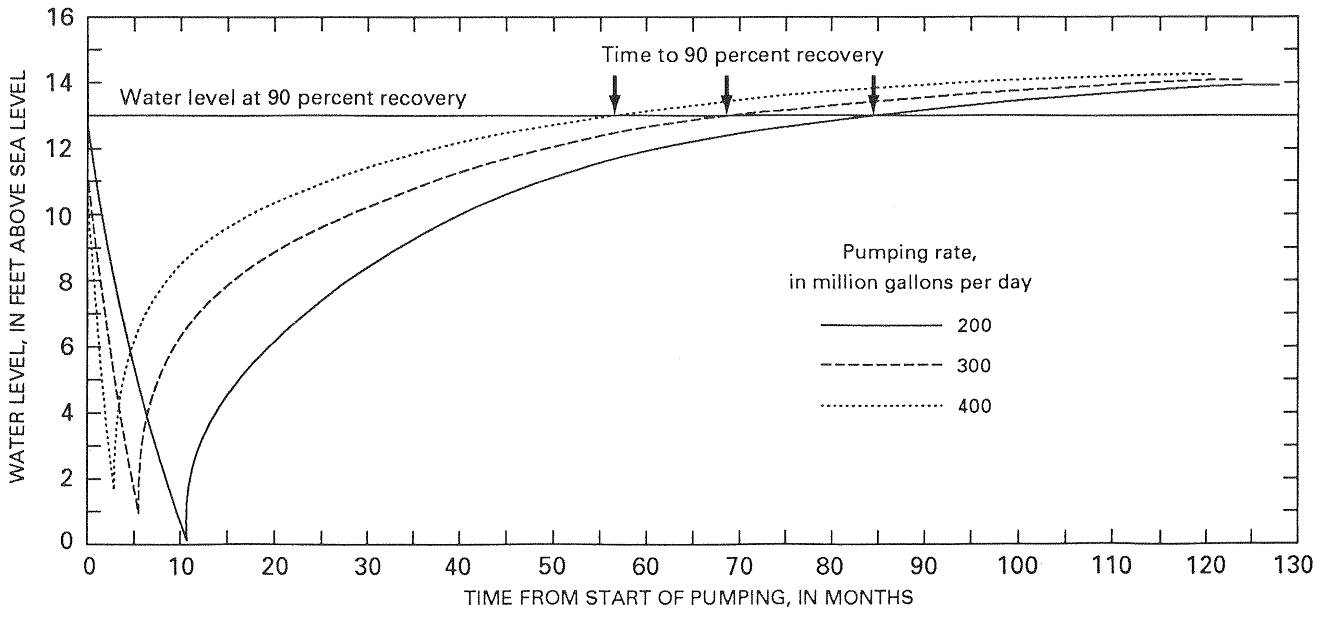


Figure 19. Average simulated head among ten representative model cells during short-term pumping at rates of 200, 300, and 400 million gallons per day with natural recovery. (Locations of cells shown in figure 18.)

Table 4. Characteristics of short-term ground-water pumping under "full-reservoir" conditions

Pumping rate (million gallons per day)	Maximum allowed duration (months)	Total volume pumped (billion gallons)	90-percent recovery: Natural recovery (years)	90-percent recovery: Artificial recharge (months)	Maximum decrease in boundary discharge (million gallons per day)
200	10.6	64.5	6.3	33.4	35.3
300	5.2	47.7	5.4	26.8	26.9
400	3.1	37.2	4.7	28.9	21.3

Thereafter, the amount diverted from the boundaries increases. When pumping stops, only 5 percent of the total volume of water pumped represents decreased boundary discharge, but, even as water levels recover and as the water removed from storage is replaced, discharge at the system boundaries remains less than its initial rate until ground-water levels recover completely. At that time, the total volume of the decrease in boundary discharge equals the total volume of water pumped.

The decrease in boundary discharge for the 300-Mgal/d pumping scenario throughout pumping and recovery is depicted in figure 23B. The maximum reduction was 26.9 Mgal/d, which occurred about 145 days after pumping stopped. Thus, pumping at a rate of 300 Mgal/d for 5.2 months would not decrease the maximum rate of boundary discharge by more than 26.9 Mgal/d (less than 10 percent of the pumping rate). The maximum decrease in the rate of boundary discharge during the 200- and 400-Mgal/d simulations was 35.3 and 21.3 Mgal/d, respectively. As observed during the analysis of recent stressed conditions, pumping for a longer duration allowed the system to more closely approach equilibrium and, thereby, to derive a larger percentage of pumping from boundary flow.

Artificial recharge augments storage and boundary discharge to a lesser extent under "full-reservoir" conditions than under recent stressed conditions, primarily because the total volume pumped under "full-reservoir" conditions is much greater and the volume available for recharge remains the same--100 Mgal/d for 60 days (6 billion gal) in an average year. The cumulative volume of water pumped and the proportion from each source during the 300-Mgal/d simulation with artificial recharge is plotted in figure 24A. The recharged water goes immediately to replenish storage and ultimately decreases the total volume of lost boundary discharge. The volume of water applied in two episodes of artificial recharge decreases the total loss of boundary discharge by 25.1 percent--from 47.7 to 35.7 billion gal. Artificial recharge does not affect the maximum loss in the rate of boundary discharge (fig. 26B) because the maximum loss occurs before the start of artificial recharge. However, artificial recharge does mitigate the total volume of water derived from decreased boundary flow through the pumping and recovery cycle.

Evaluation and Summary of Pumping Strategy

The conjunctive use water-supply strategy described in this report employs short-term intensive ground-water pumping in Brooklyn and Queens to supplement the supply from New York City's upstate reservoir system

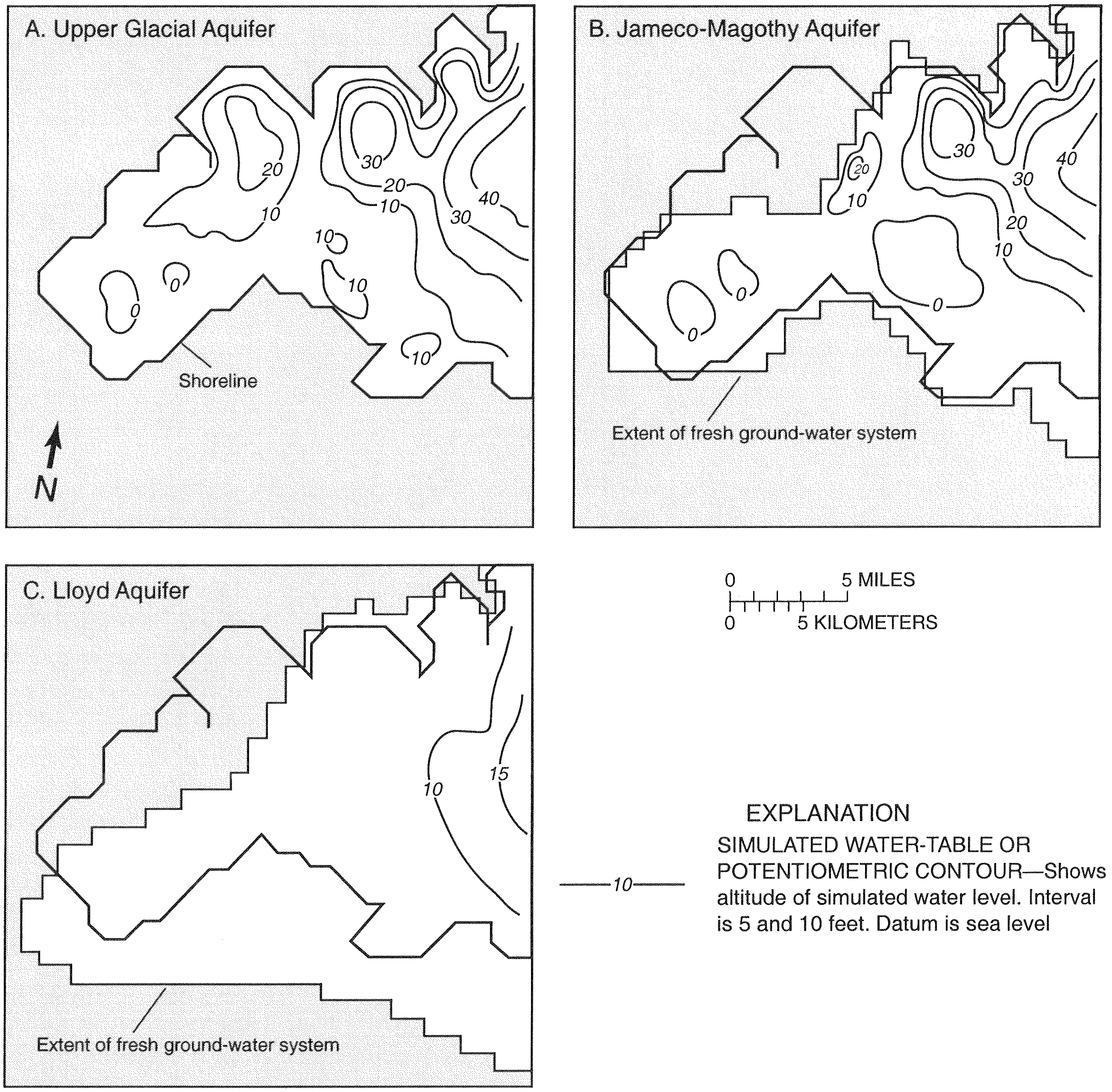


Figure 20. Distribution of hydraulic head in western Long Island after pumping at 300 million gallons per day for 5.2 months during "full-reservoir" conditions. (The location of pumping centers is shown in figure 18.)

during periods of drought. This strategy minimizes drawdown, the attendant decrease in discharge to the natural boundaries of the system (stream, wetlands, brackish-water bays), and the landward movement of the saltwater-freshwater interface in the confined aquifers. Inspection of the pumping and natural recovery phases in simulated hydrographs shows that, although the tested scenarios would draw water levels down to near sea level, they would be at that level for only a short time (figs. 10, 19).

An analysis of the amount of water removed from storage and system boundaries showed that the total volume of water pumped is derived from a corresponding decrease in the total volume of boundary discharge. However, the decrease would be dispersed through the

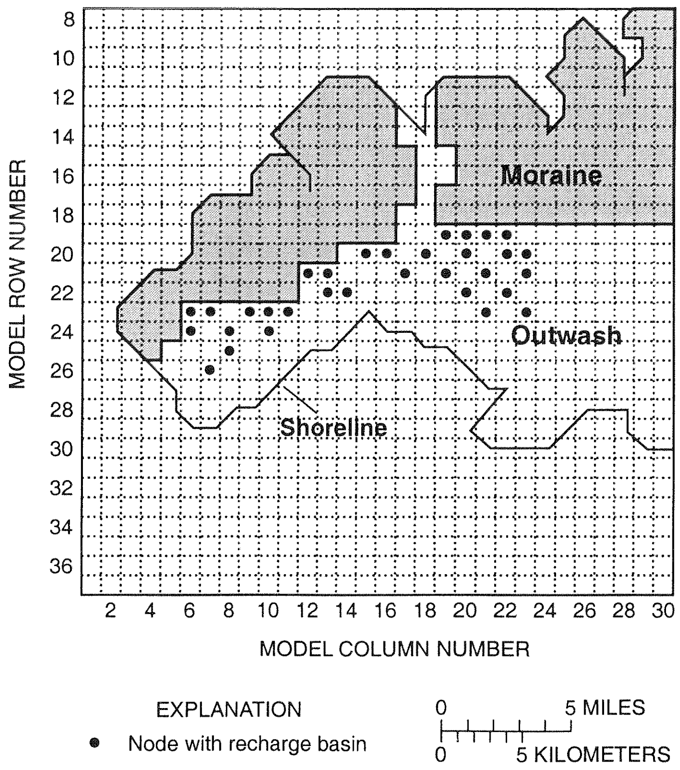


Figure 21. Locations of recharge basins used to accelerate recovery of ground-water levels after pumping under "full-reservoir" conditions.

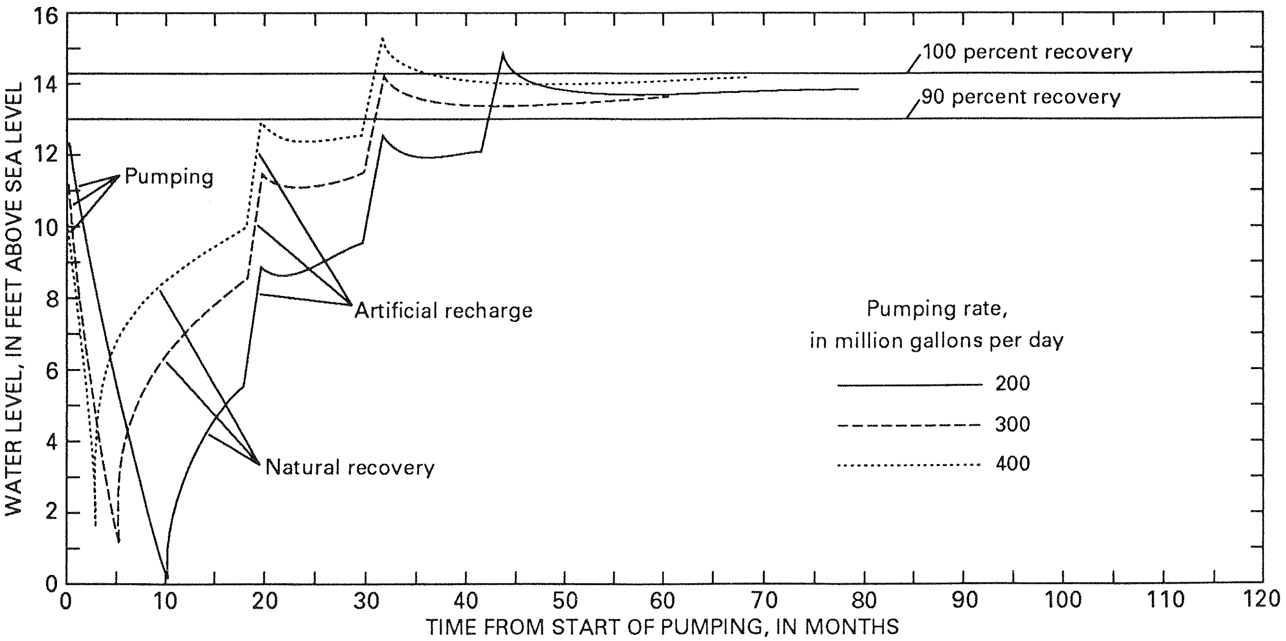


Figure 22. Average simulated head among ten representative model cells during short-term pumping at 200, 300, and 400 million gallons per day with recovery accelerated by artificial recharge.

period of pumping and recovery. Furthermore, the maximum decrease in the rate of boundary discharge is only a small percentage of the pumping rate.

For pumping scenarios under stressed conditions, the maximum decrease in boundary discharge ranged from 7 percent of the pumping rate, for the 150-Mgal/d scenario, to about 30 percent, for the 50 Mgal/d scenario. For pumping scenarios under "full-reservoir" conditions, the maximum decrease in boundary discharge ranged from 5 percent of the pumping rate, for the 400-Mgal/d scenario, to 18 percent, for the 200-Mgal/d scenario. The maximum decrease in boundary discharge is higher for lower pumping rates because lower pumping rates are maintained longer; cause a broader cone of depression; and cause greater drawdown near the boundaries. This is supported by the greater volume of water removed from storage at lower pumping rates.

The potential frequency of use of the pumping scenarios described herein is a major consideration in the development of a long-range conjunctive use plan for the city of New York because droughts are expected to recur periodically. The simulation results indicate that pumping scenarios under stressed conditions could be implemented every 6 or 7 years with natural recovery, whereas the same scenarios could be implemented every 2 or 3 years using artificial recharge. Pumping scenarios under the "full-reservoir" condition could be implemented every 5 to 8 years with natural recovery, whereas the same scenarios could be implemented every 3 to 4 years using artificial recharge.

For natural recovery scenarios, implementation of a subsequent ground-water supplement at 90 percent recovery will yield slightly less total volume of water before critical drawdown levels are reached. Use of artificial recharge, however, should allow almost full recovery and permit subsequent scenarios at full capacity.

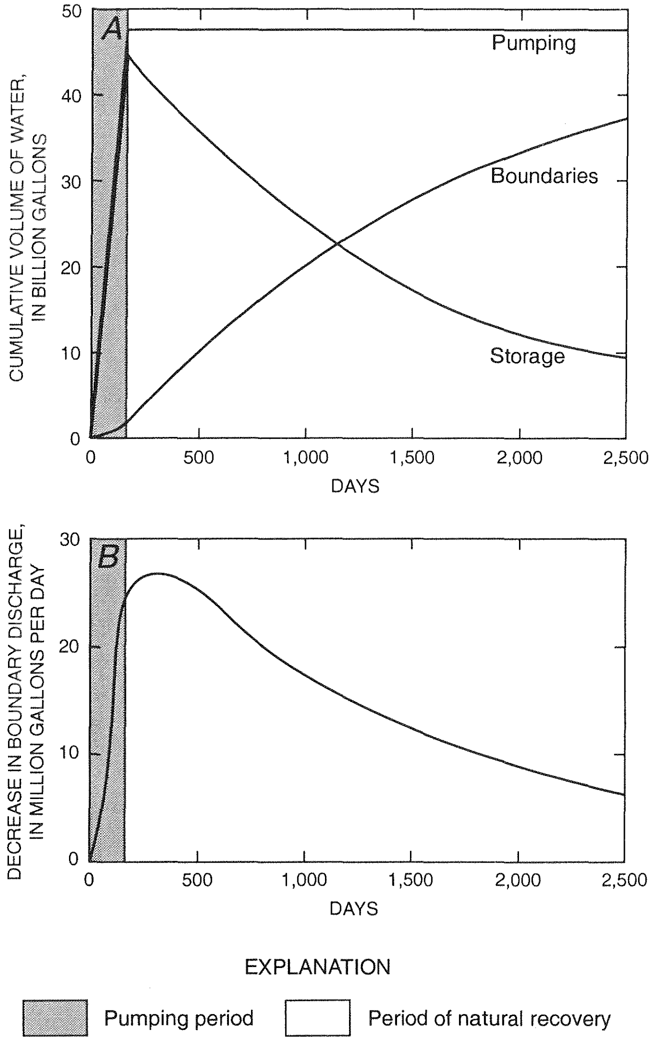


Figure 23. Ground-water budget during 5.2 months of pumping at 300 million gallons per day with natural recovery. A, Cumulative volume of water removed from storage and discharge boundaries. B, Decrease in boundary discharge.

The range of pumping scenarios given for the stressed and "full-reservoir" conditions offer different advantages. The estimated application of two alternative pumping scenarios under "full-reservoir" conditions for the 1980-81 drought are compared in figure 25. The pumping of 200 Mgal/d to supplement the surface-water supplies is estimated to have reduced the draft from upstate reservoirs by that rate for a period of 10.6 months, leaving the reservoir system with an additional 64.5 billion gal at the end of pumping (fig. 25A). This would have increased reservoir levels by about 4 percent at the time of lowest reservoir levels in the drought (January-February 1981) but would have augmented the reservoir system by 11.2 percent of its storage capacity by the end of pumping. In general, the reservoirs reach capacity and spill over during April, May, and June, but after the 1980-81 drought, they failed to reach 90-percent capacity (fig. 25A) making the reservoir system more susceptible to drought in the following year.

The 400-Mgal/d pumping scenario would have reduced the draft on the reservoir system by that rate for a period of 3.1 months, leaving the reservoir system with an additional 37.2 billion gal by the end of pumping. However, it would have augmented the reservoir system by 6.5 percent of storage capacity at the point of critically low reservoir levels in January 1981 (fig. 25B).

The analysis described herein is intended to:

1) Demonstrate the hydrologic advantages of a short-term pumping strategy (pumping intermittently at high rates for short duration);

2) Provide a qualitative comparison of various pumping rates and durations and their simulated effects; and

3) Give general indications of feasible pumping rates, the distribution of pumping centers, allowed pumping durations, and practical frequencies of use.

The accuracy of model simulation of hypothetical conditions is difficult to define. The sensitivity of the ground-water system demonstrated using the series of numerical simulations presented herein provides a conceptual basis for the design of a conjunctive-use supplemental water-supply strategy for the City of New York.

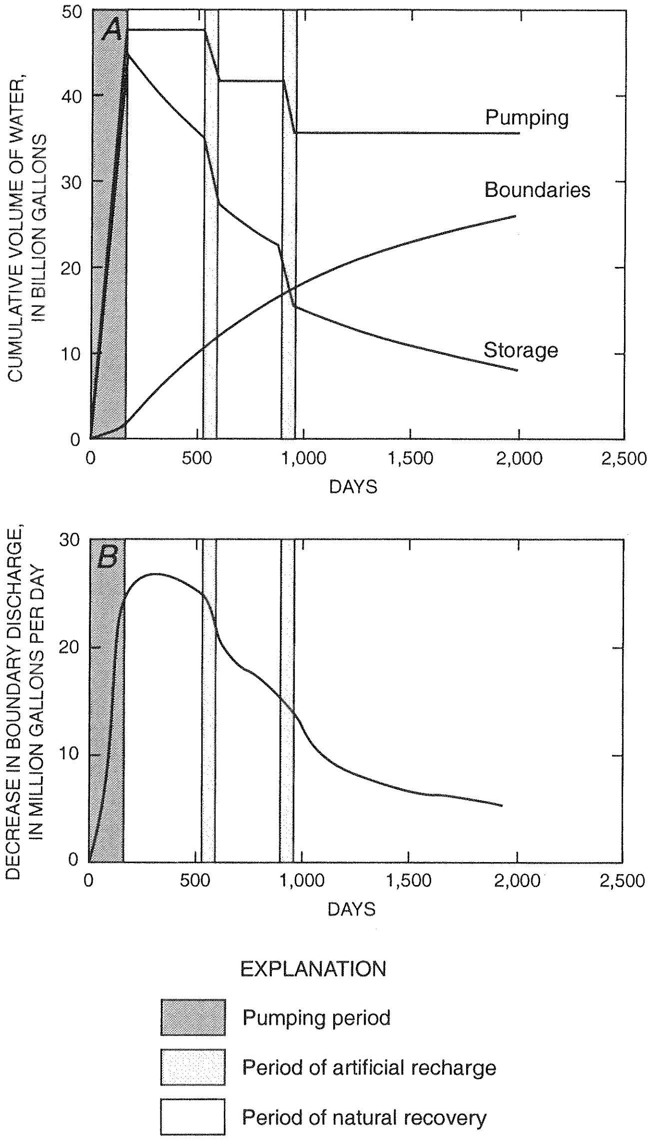


Figure 24. Ground-water budget during 5.2 months of pumping at 300 million gallons per day with recovery accelerated by artificial recharge. A, Cumulative volumes of water removed from storage and discharge boundaries. B, Decrease in boundary discharge.

CONCLUSIONS

The use of ground water to supplement New York City's surface-water supply is hydraulically feasible, offers a means to minimize surface-water shortages during short-term droughts, and could reduce the required resevoir-storage capacity of a strictly surface-water supply system. Short-term intensive ground-water pumping followed by a period of water-level recovery

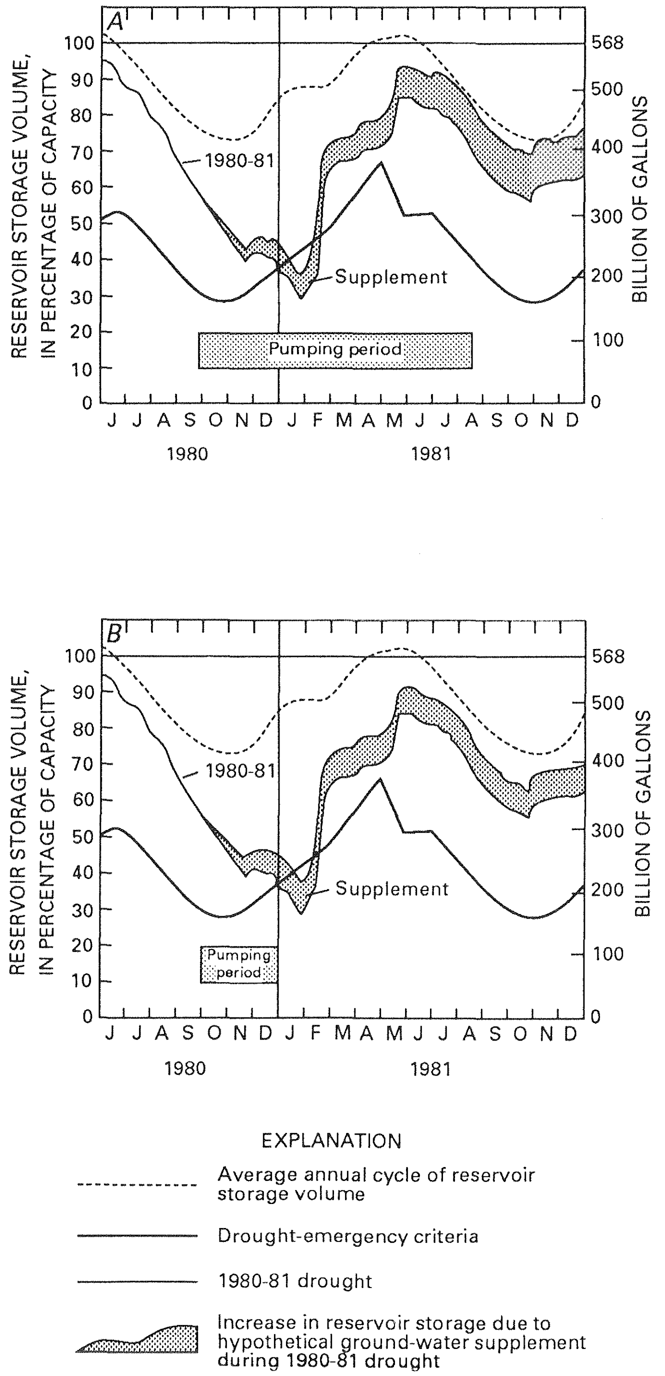


Figure 25. Composite storage capacity of the New York City surface-water reservoirs from June 1980 through December 1981 and the projected effect of supplemental ground-water pumping. A. At 200 million gallons per day for 10.6 months. B. At 400 Mgal/d for 3.1 months.

would minimize the effects of drawdown on the ground-water system by dispersing the decreases in boundary discharge over the entire period of pumping and recovery, and would allow ground water to be supplied at high rates during times of maximum need. Artificial recharge using surplus surface water appears to be a practical method of increasing the rate of recovery and maintaining the frequency and magnitude of ground-water supplement through consecutive drought periods. Flexibility in pumping rate and duration would allow adjustment to meet the needs of the specific drought emergency. The options range from supplying an immediate source of water at a high rate during times of critically low reservoir levels to supplying a supplement of moderate rate and larger total volume that emphasizes reservoir recovery to year-end capacity before the next dry season.

The economics of well-field design, installation of pumping centers, and development of water-treatment facilities would be a major consideration in the development and the design of a conjunctive use system, but these were beyond the scope of the analysis.

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